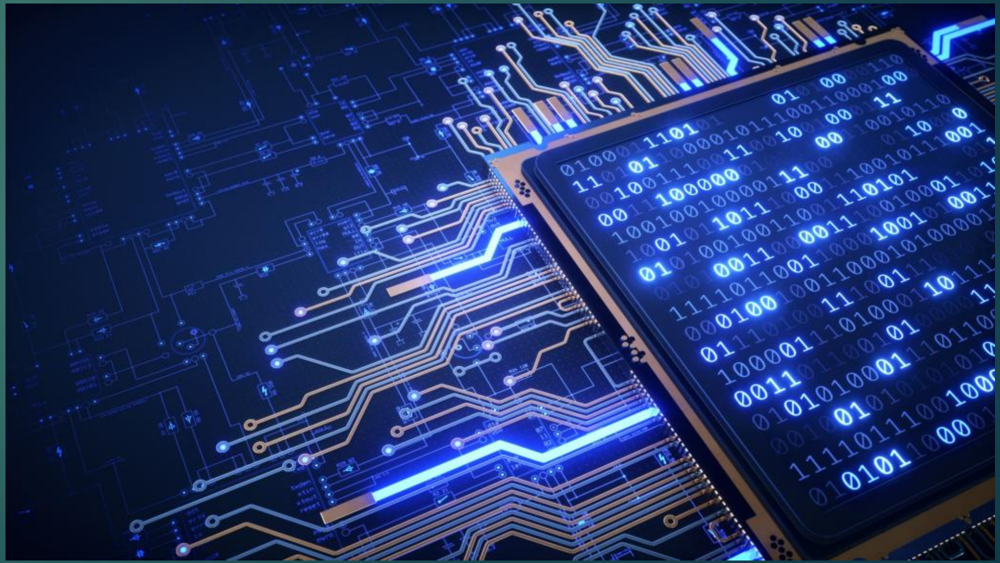
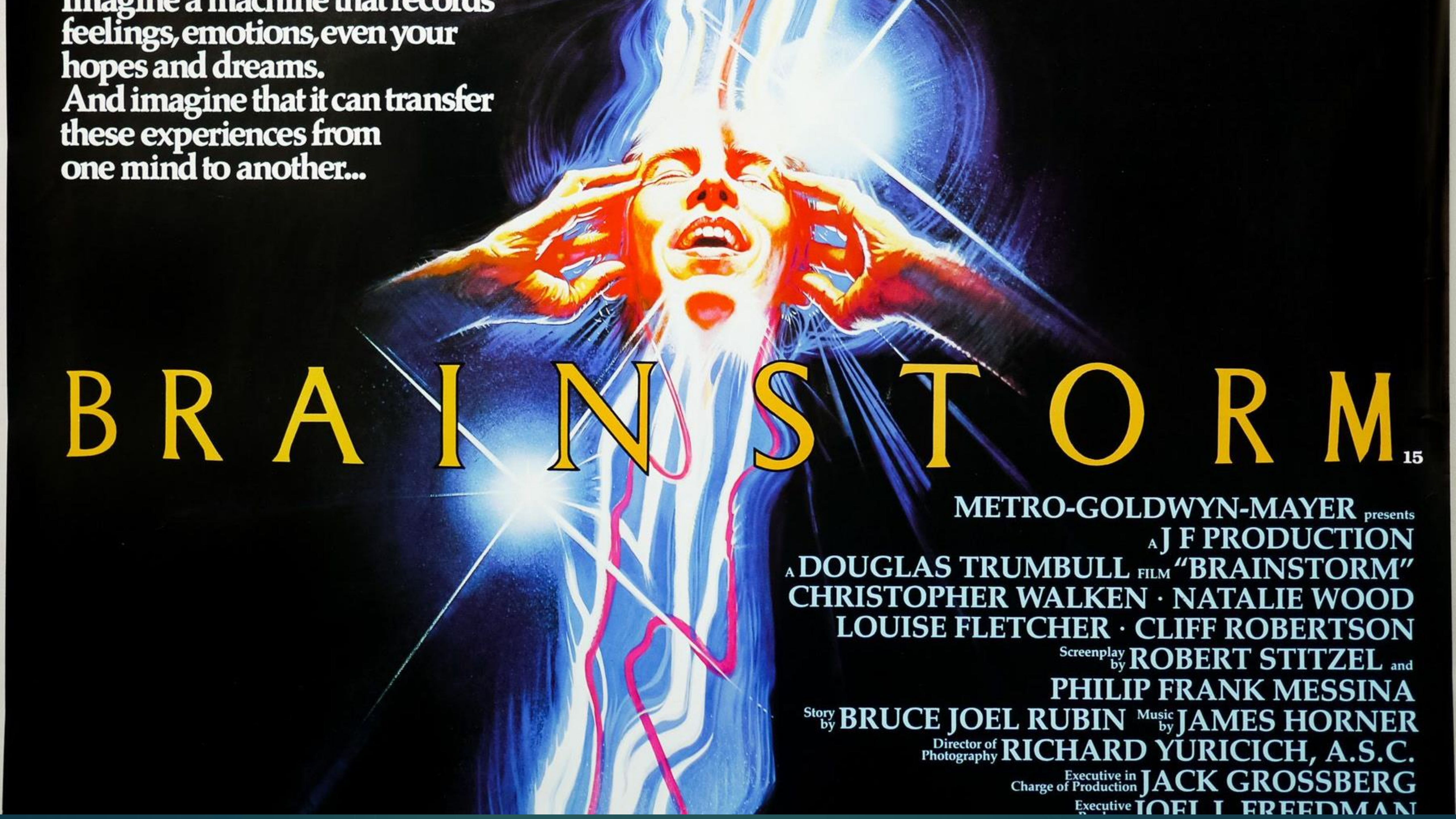
Brain Computer Interaction

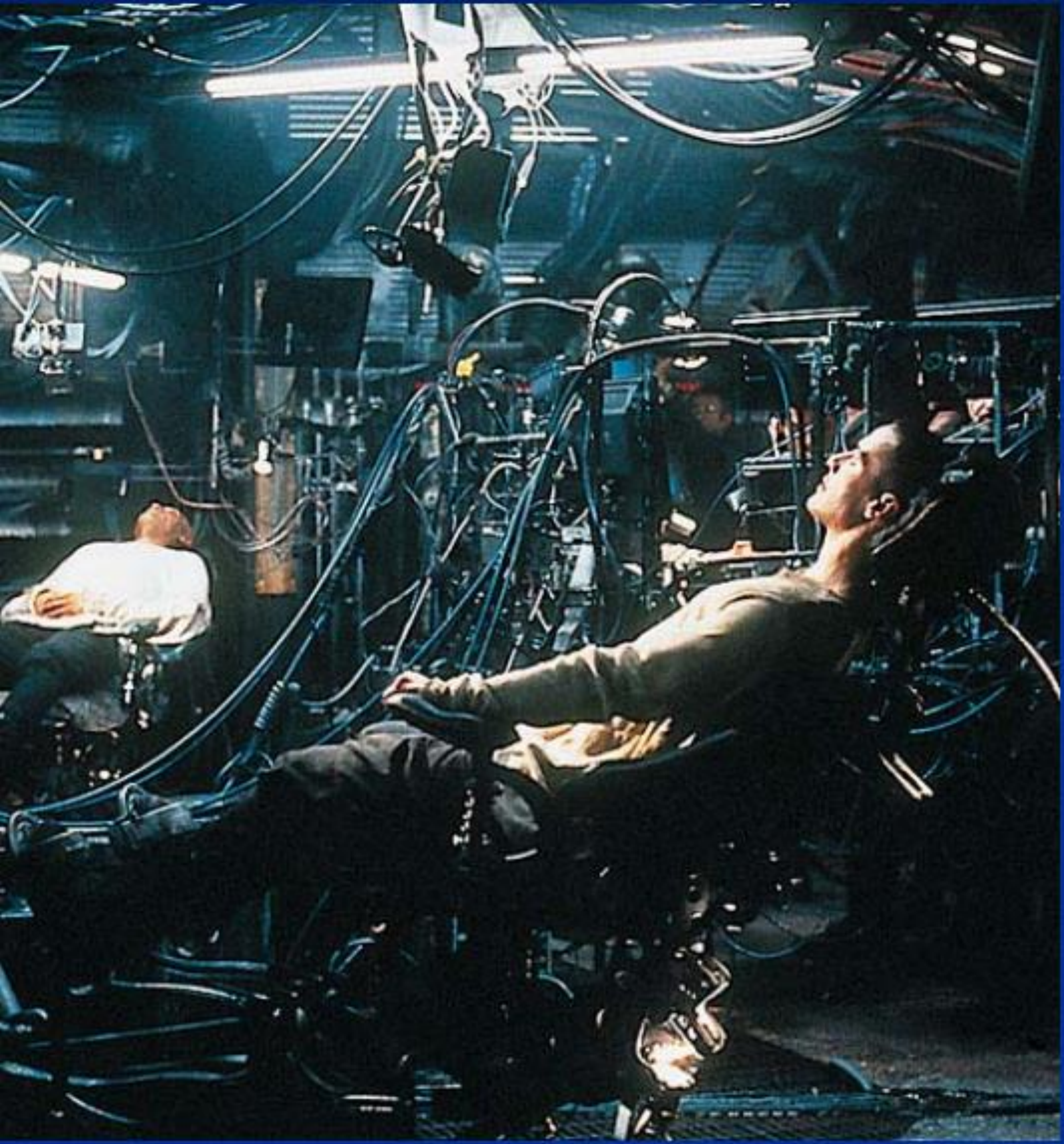


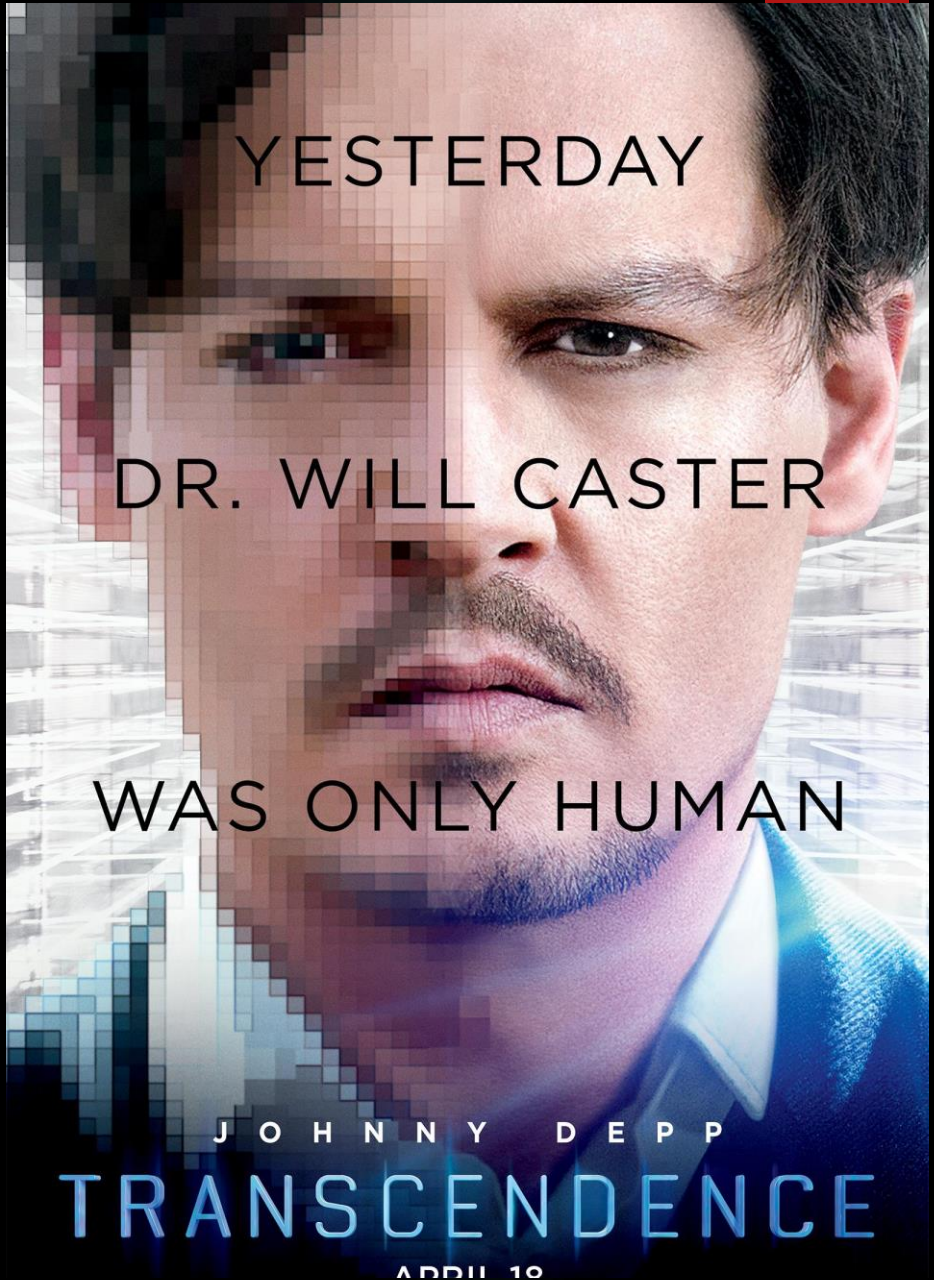
Introduction to BCI

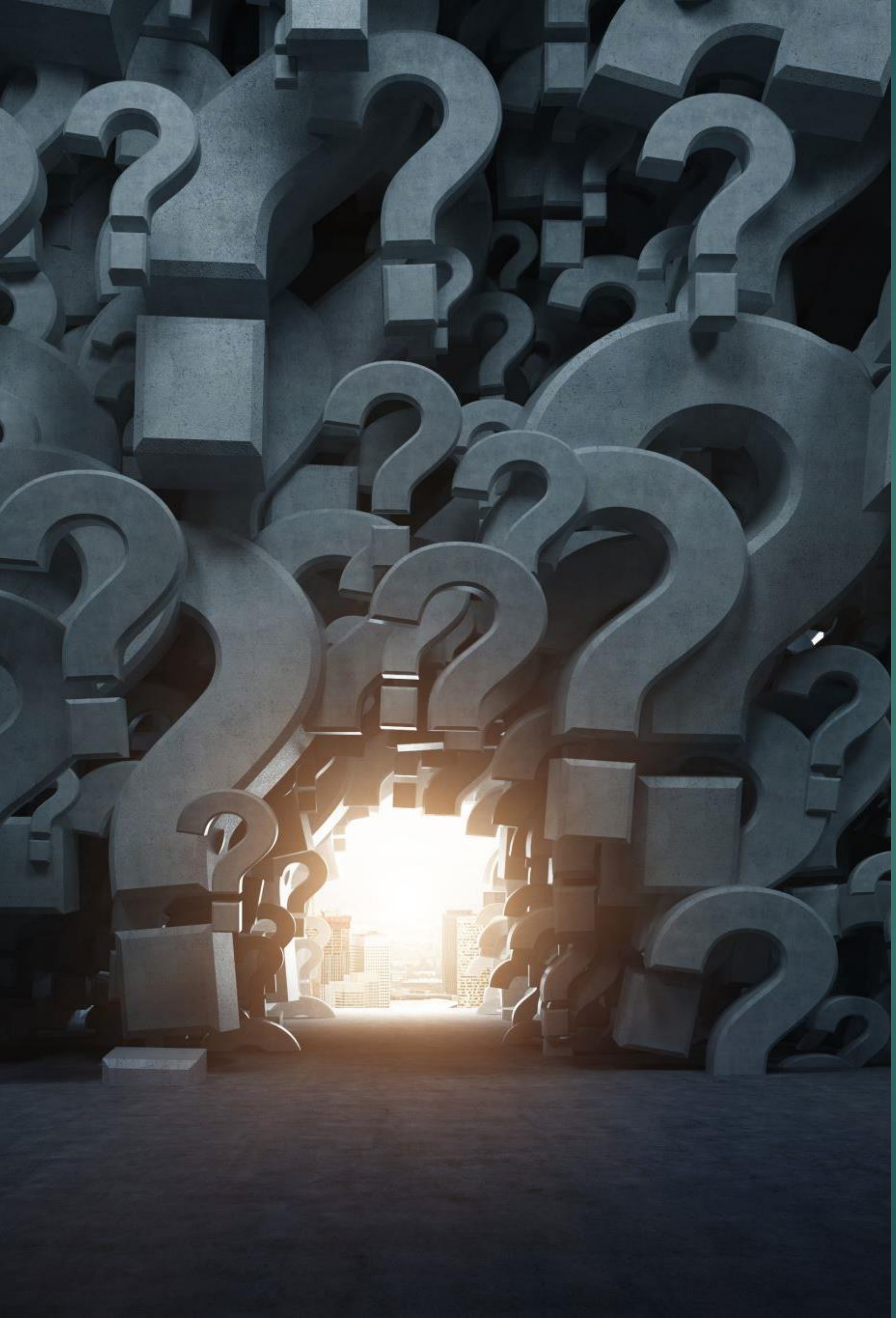
What's Today

- The Course Content
- What is Brain Computer Interaction
- History of BCI


feelings, emotions, even your
hopes and dreams.
And imagine that it can transfer
these experiences from
one mind to another...
BRAINSTORM
15
METRO-GOLDWYN-MAYER presents
A J F PRODUCTION
A DOUGLAS TRUMBULL FILM "BRAINSTORM"
CHRISTOPHER WALKEN · NATALIE WOOD
LOUISE FLETCHER · CLIFF ROBERTSON
Screenplay by ROBERT STITZEL and
PHILIP FRANK MESSINA
Story by BRUCE JOEL RUBIN Music by JAMES HORNER
Director of Photography RICHARD YURICICH, A.S.C.
Executive in Charge of Production JACK GROSSBERG




YESTERDAY
DR. WILL CASTER
WAS ONLY HUMAN
JOHNNY DEPP
TRANSCENDENCE



Is it FICTION or is it POSSIBLE???

Syllabus

Unit – 1 *Introduction to Brain Computer Interface*

Unit – 2 *Introduction to Basic Neuroscience*

Unit – 3 *Modelling and Recoding of the Brain Signals*

Unit – 4 *Signal processing*

Unit – 5 *Signal Analysis using Machine Learning Approaches*

Unit – 6 *BCI Applications*

Course Assessment

- Mid Sem
- End Sem
- Quizzes
  - Surprise Quiz
  - Scheduled Quiz
- Projects
  - Knowledge of Python or MATLAB required

Motivation for BCIs

- Potential for restoring lost sensory and motor function
- To control prosthetic devices such as prosthetic arms or legs for amputees and patients with spinal-cord injuries
- Wheelchairs for paralyzed individuals
- Cursors and word spellers for communication by locked-in patients
- Sensory prosthetic devices such as cochlear implant for the deaf, retinal implant for the blind
- More recently, researchers have begun exploring BCIs for able-bodied individuals for a host of applications such as Game, Entertainment to robotic avatars, biometric identification and Education.

Users

Language illiterate

Novice user

Blind user

Old-age people

Disabled user

Brain Computer Interface

- A system which translates thoughts and provides an interface used for communication called as Brain Computer Interface (BCI)
- A typical BCI system comprises of signal acquisition system, signal processing (feature extraction and classification) and an output device

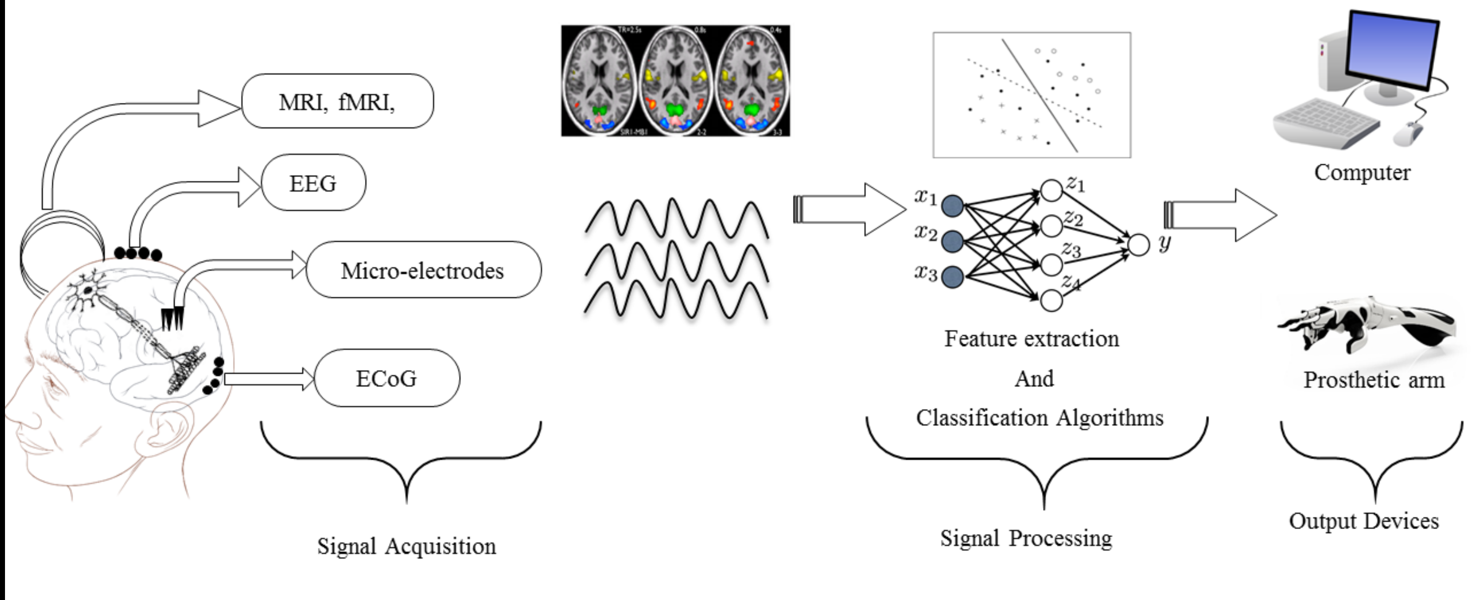
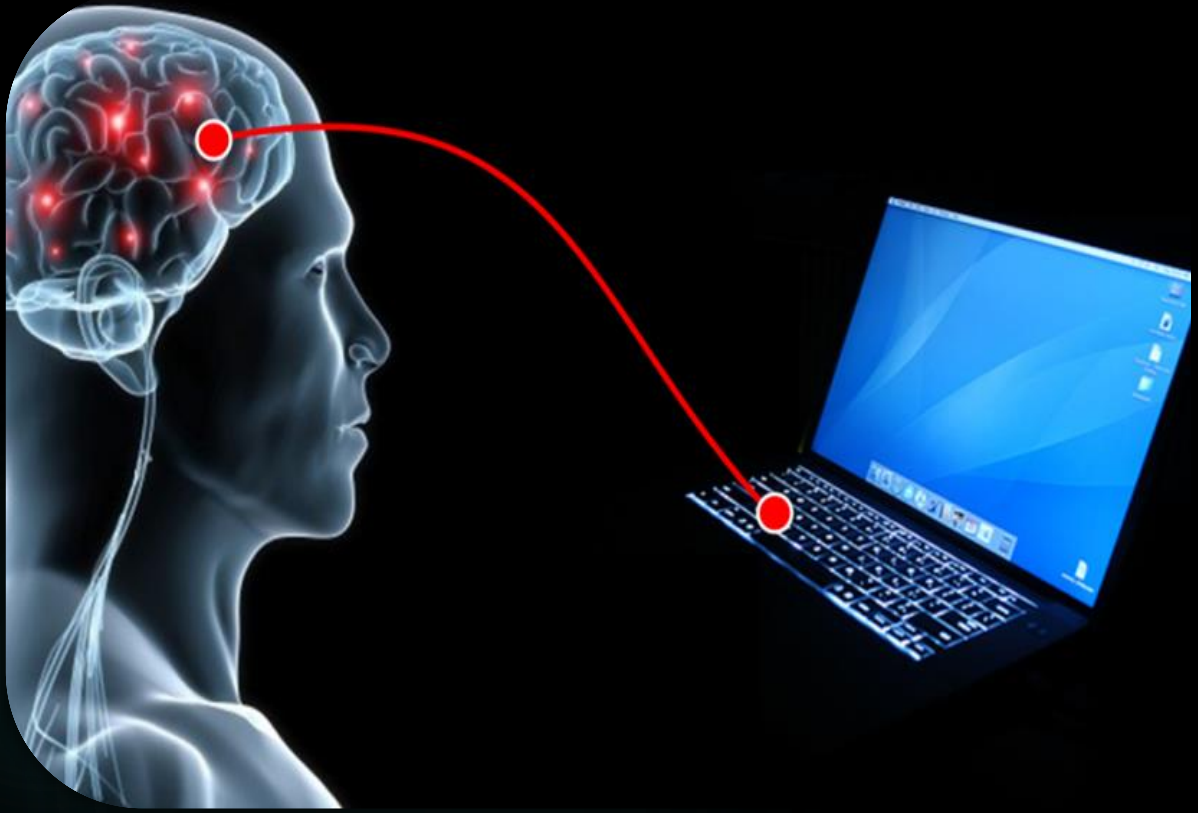
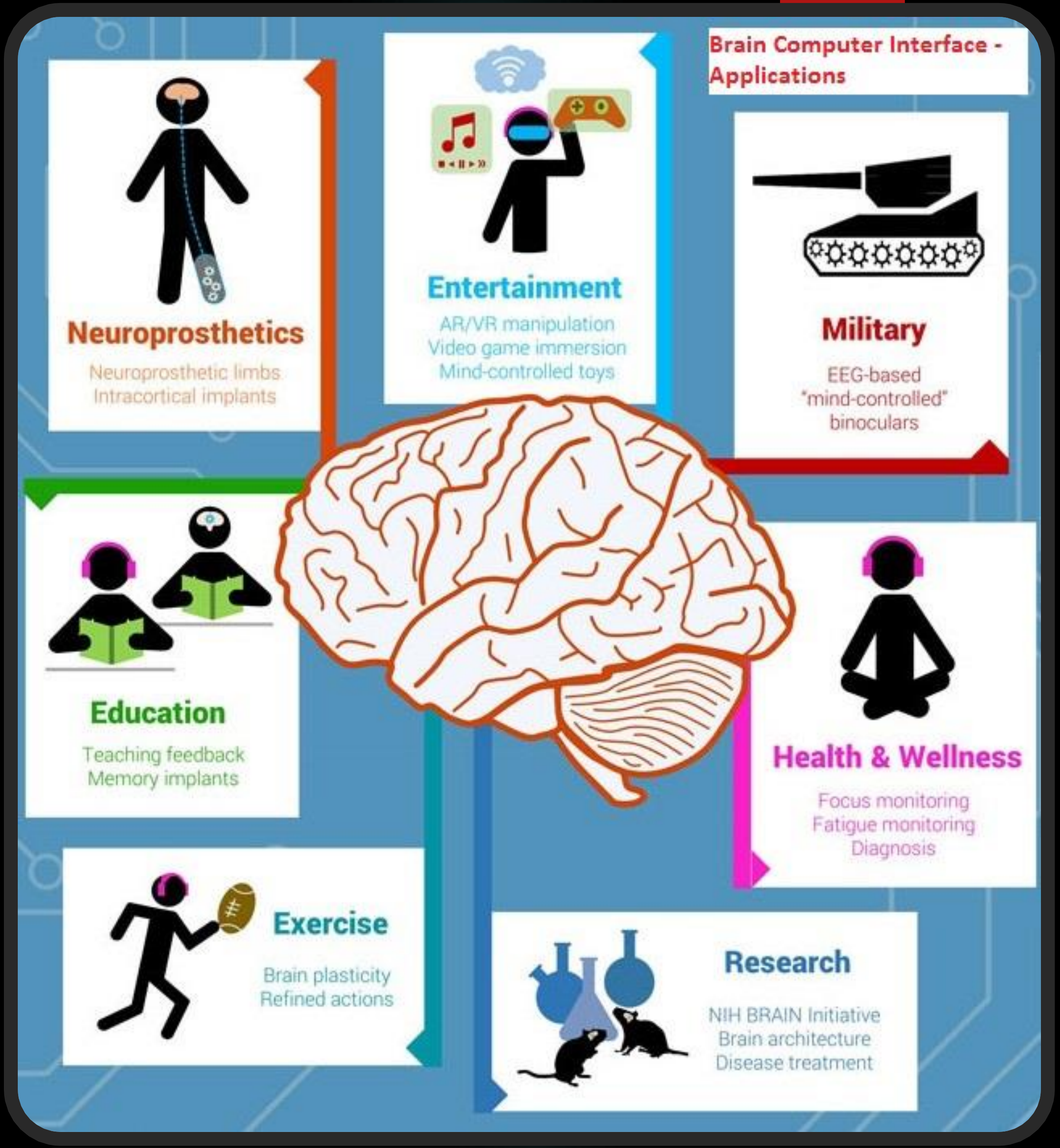


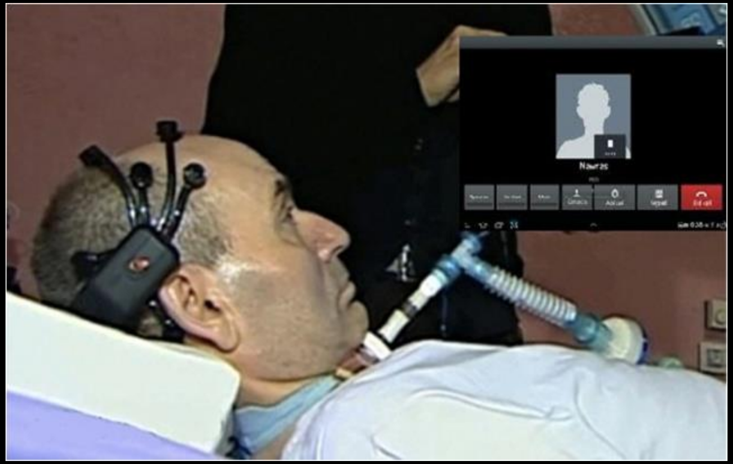
Image Credits: Bablani, Annushree, et al. "Survey on brain-computer interface: An emerging computational intelligence paradigm." ACM Computing Surveys (CSUR) 52.1 (2019): 1-32.

Brain Computer Interaction





Some real-time BCI Applications



Communication

Device Control

Attention Monitoring

Automatic Motion Controlling

Games & Entertainment

Whether BCIs will eventually become as commonplace as current human accessories for sensory and motor augmentation, such as cellular phones and automobiles.????

That remains to be seen.

There are several moral and ethical challenges that society will need to address

History of Brain Computer Interaction

Timeline of BCI

1875

Electrical impulses from a living brain of a rabbit and monkey were recorded for the first time by Richard Caton

1890

Adolf Beck studied the brain activity of animals in response to sensory simulation

1913

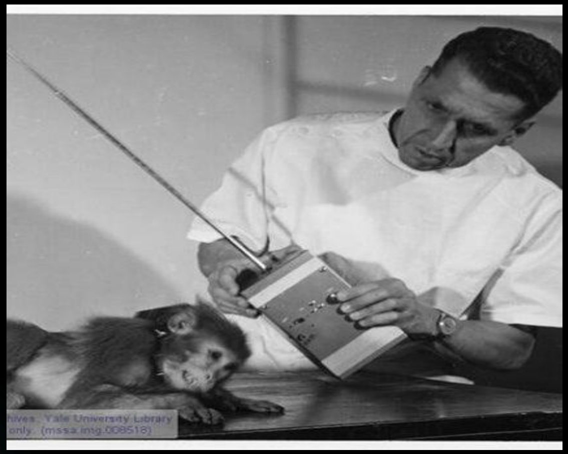
Napoleon Cybulski studied the flow of electric current in muscles using his own capacitor.

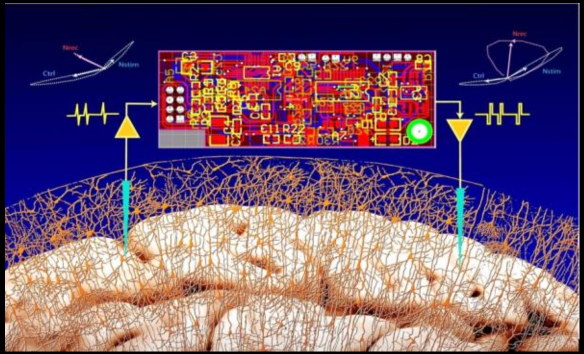
1920

Hans Berger recorded EEG signals from the lesion area of the human scalp for the first time using a Siemens double-coil galvanometer and non-polarized electrodes.

1969

Delgado developed an implantable chip (which he called a "stimoceiver") that could be used to both stimulate the brain by radio and send electrical signals of brain activity by telemetry, allowing the subject to move about freely.





1969

Dr. Eberhard Fetz showed that neural activity could be used to drive an external device.

1973

Vidal in 1973 explored the use of scalp-recorded brain signals in humans to implement a simple noninvasive BCI based on "visually evoked potentials"

1990

Philip Kennedy had in 1990 developed "invasive" human brain-computer interface, wires inside the brain attached to a computer.

2001

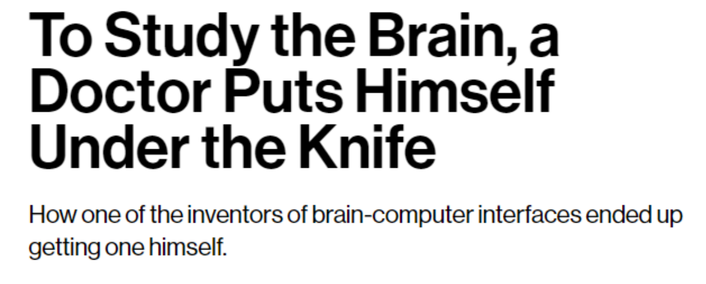
John Donoghue and his team of Brown University in 2001, commercially design a brain computer interface, the so-called BrainGate.

2004

In 2004, Jonathan Wolpaw and researchers at New York State Department of Health's Wadsworth Center demonstrated the ability to control a computer using a BCI.

June 2014

Phil Kennedy implanted electrodes into his brain in order to establish a connection between his motor cortex and a computer


To Study the Brain, a Doctor Puts Himself Under the Knife

How one of the inventors of brain-computer interfaces ended up getting one himself.

- More recently, researchers have begun exploring BCIs for able-bodied individuals for a host of applications such as
  - Games
  - Entertainment to robotic avatars, biometric identification,
  - and Education.

Our Goal in this course

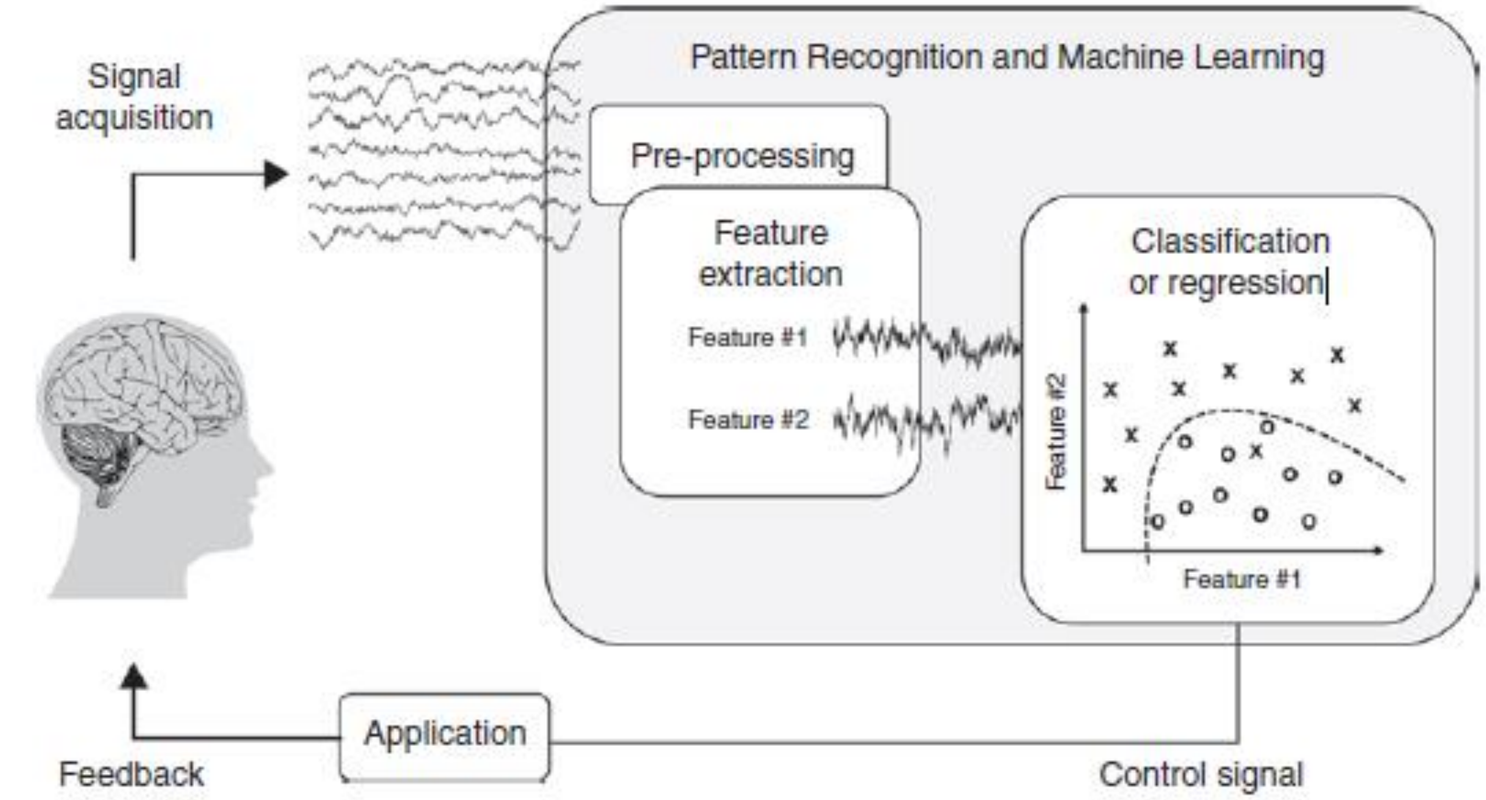


Figure 1.1. **Basic components of a brain-computer interface (BCI).** (Adapted from Rao and Scherer, 2010).

BCI Applications

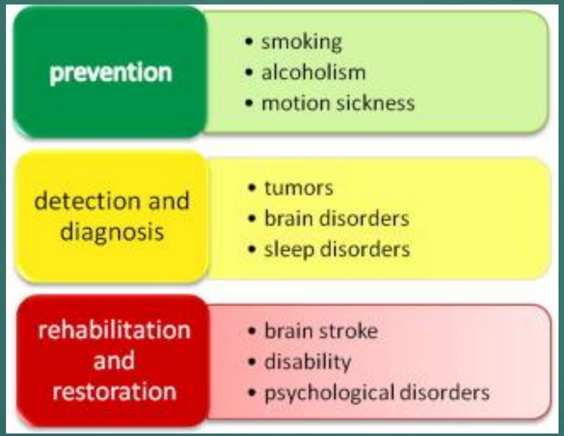
Hype Cycle for Emerging Technologies, 2020

gartner.com/SmarterWithGartner

BCI Applications

- Device Control
- User State Monitoring
- Training and Education
- Games and Entertainment.
- Cognitive improvement
- Safety and Security

Medical Applications



Device controls

- For rehabilitation
  - Prosthetic arm
  - Prosthetic legs

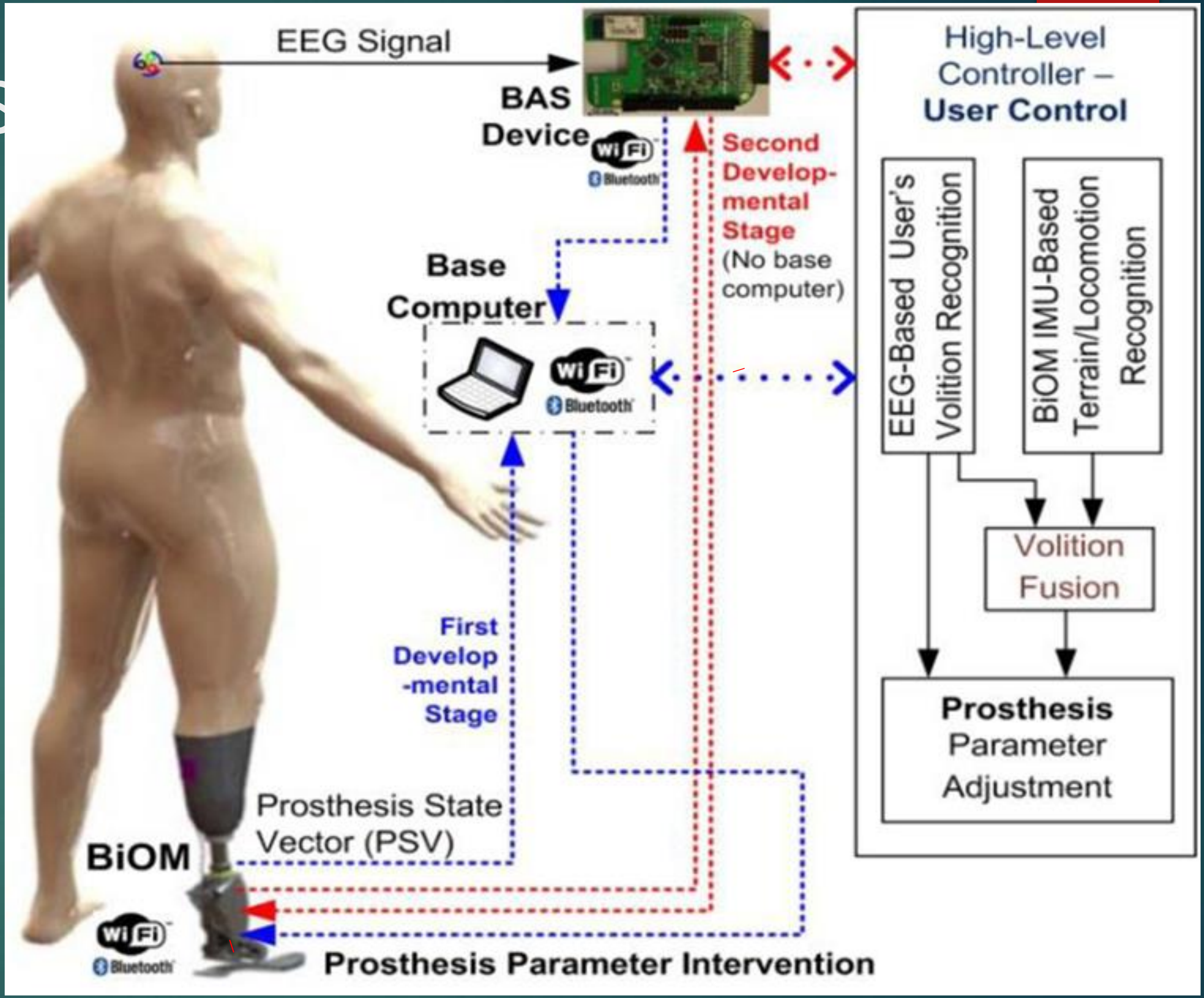
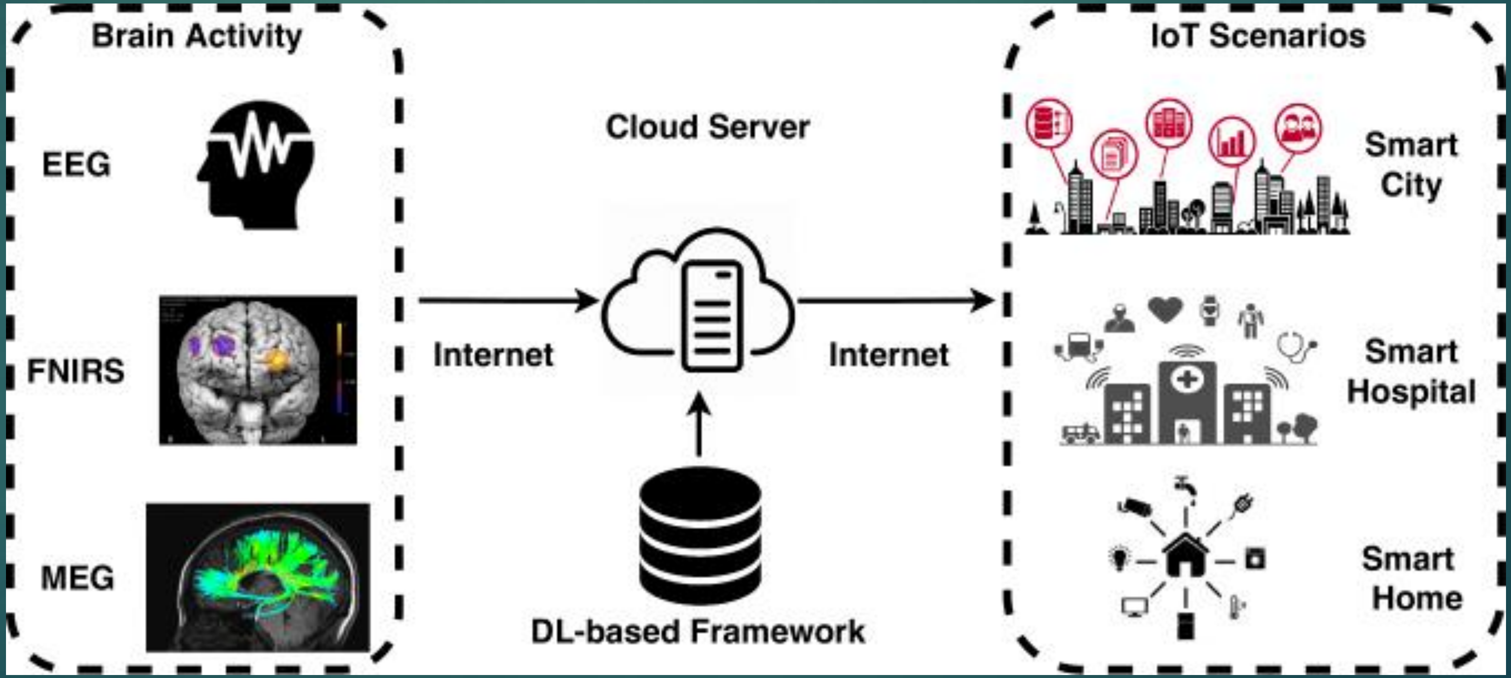


Image credits: https://www.frontiersin.org/files/Articles/308916/fneur-08-00696-HTML/image_m/fneur-08-00696-g001.jpg

Neuroergonomics and smart environment

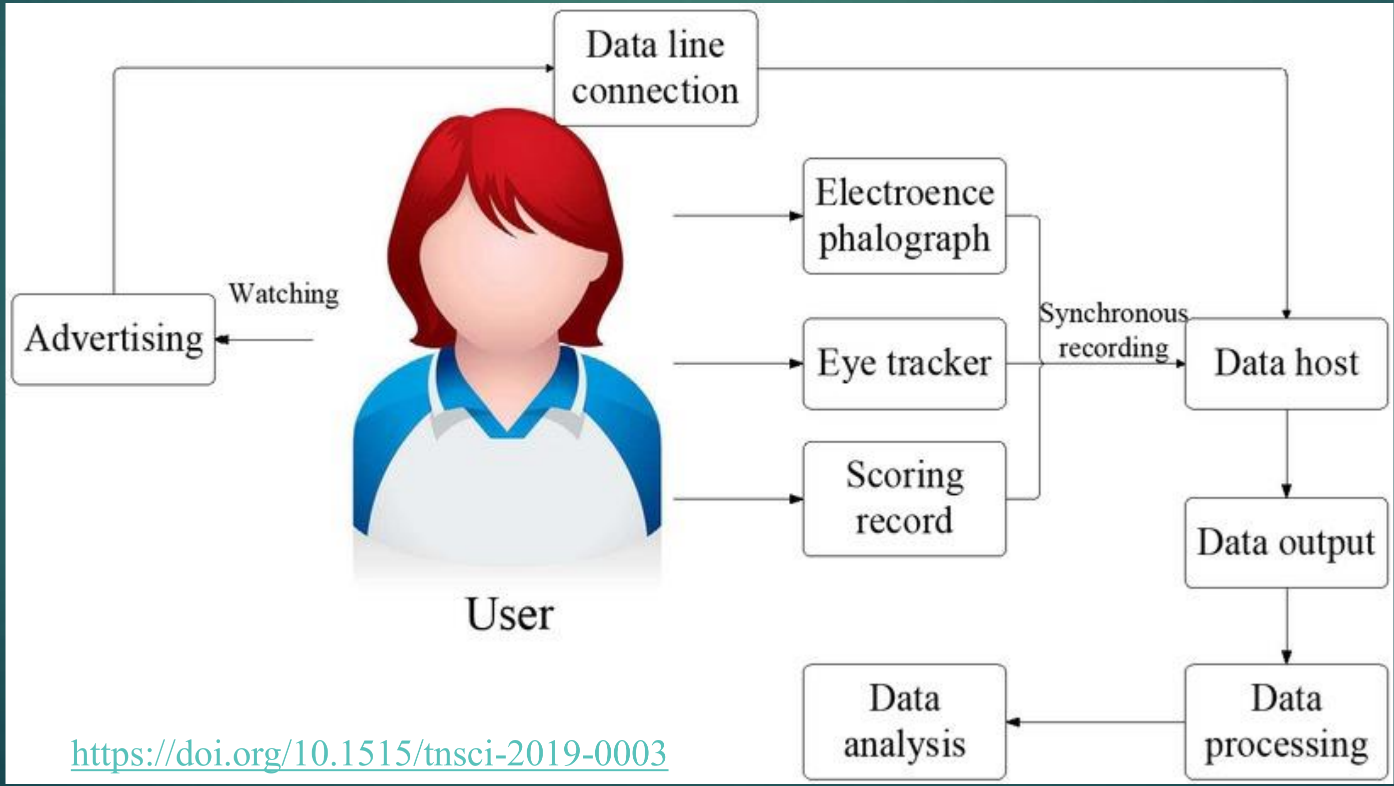
- Cooperation between Internet of Things (IOT) and BCI technologies
- intelligent transportation



by Xiang Zhang, et al. ·

Neuromarketing and advertisement

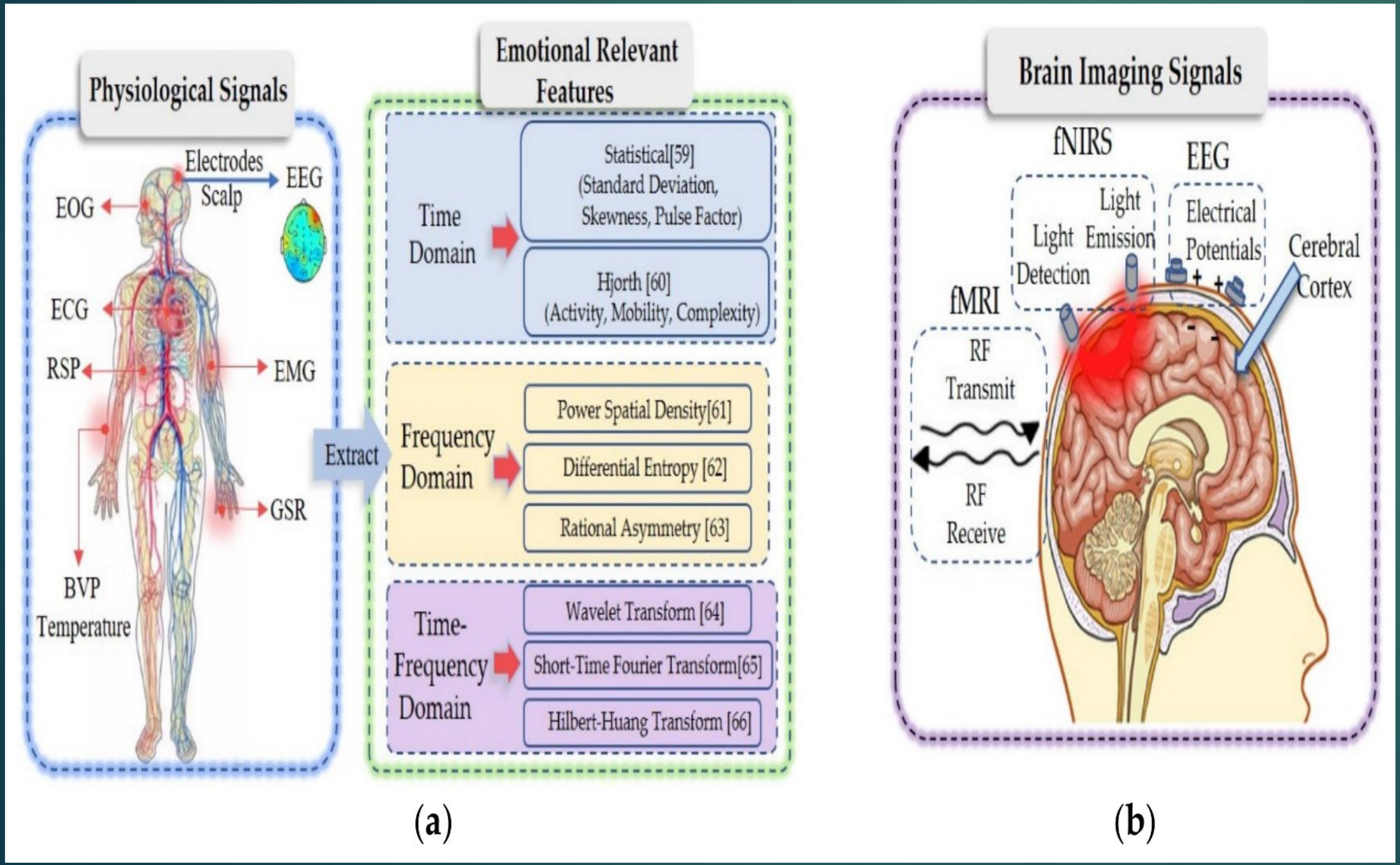
- EEG evaluation for TV advertisements related to both commercial and political fields.
  - The generated attention accompanying watching activity
  - Estimating the memorization of TV advertisements



https://doi.org/10.1515/tnsci-2019-0003

Educational and self-regulation

- Emotional regulation
  - Use of fMRI–EEG BCI to fight the depression feeling as well as other neuropsychiatric disorders



Advances in Multimodal Emotion Recognition Based on Brain–Computer Interfaces
by Zhipeng He

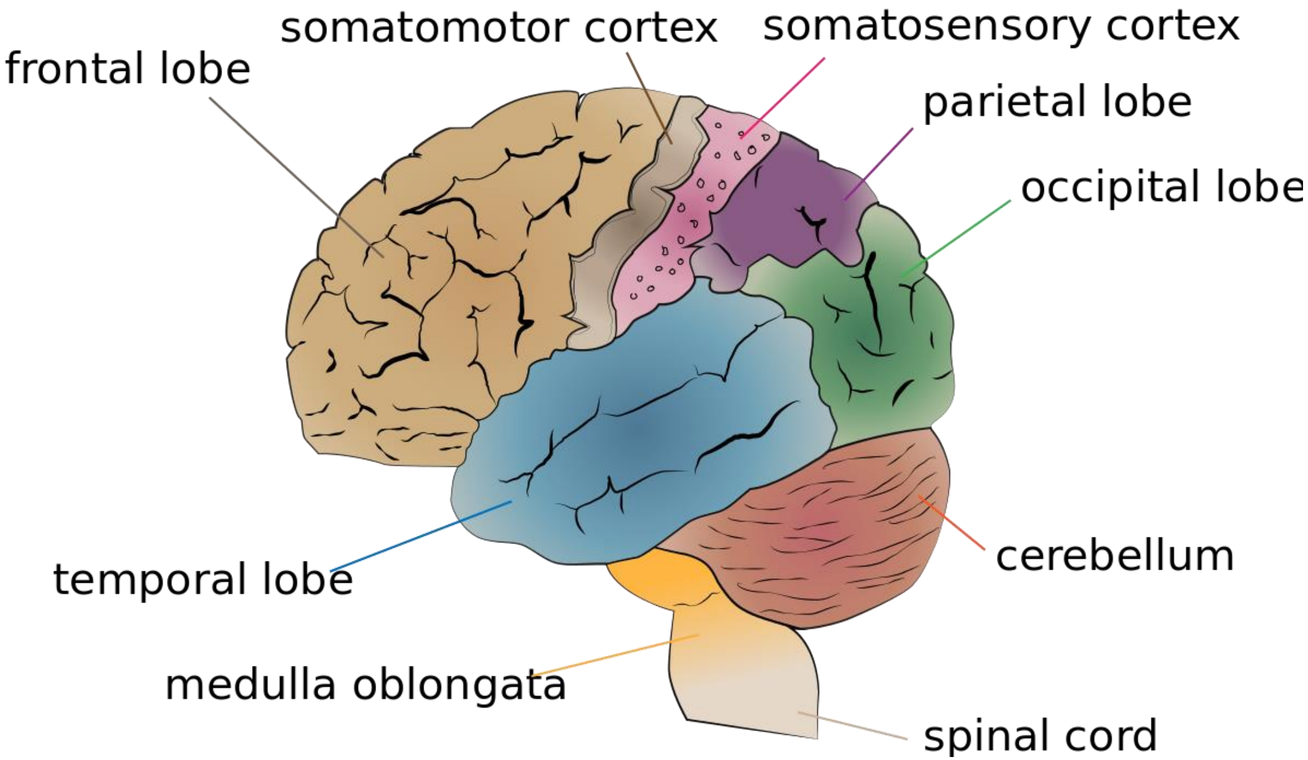
Challenges

- Usability
- Hardware
- Signal processing
- System integration
- Cost

BCI-S2022

Basics of Neuroscience for BCI

The Human Brain



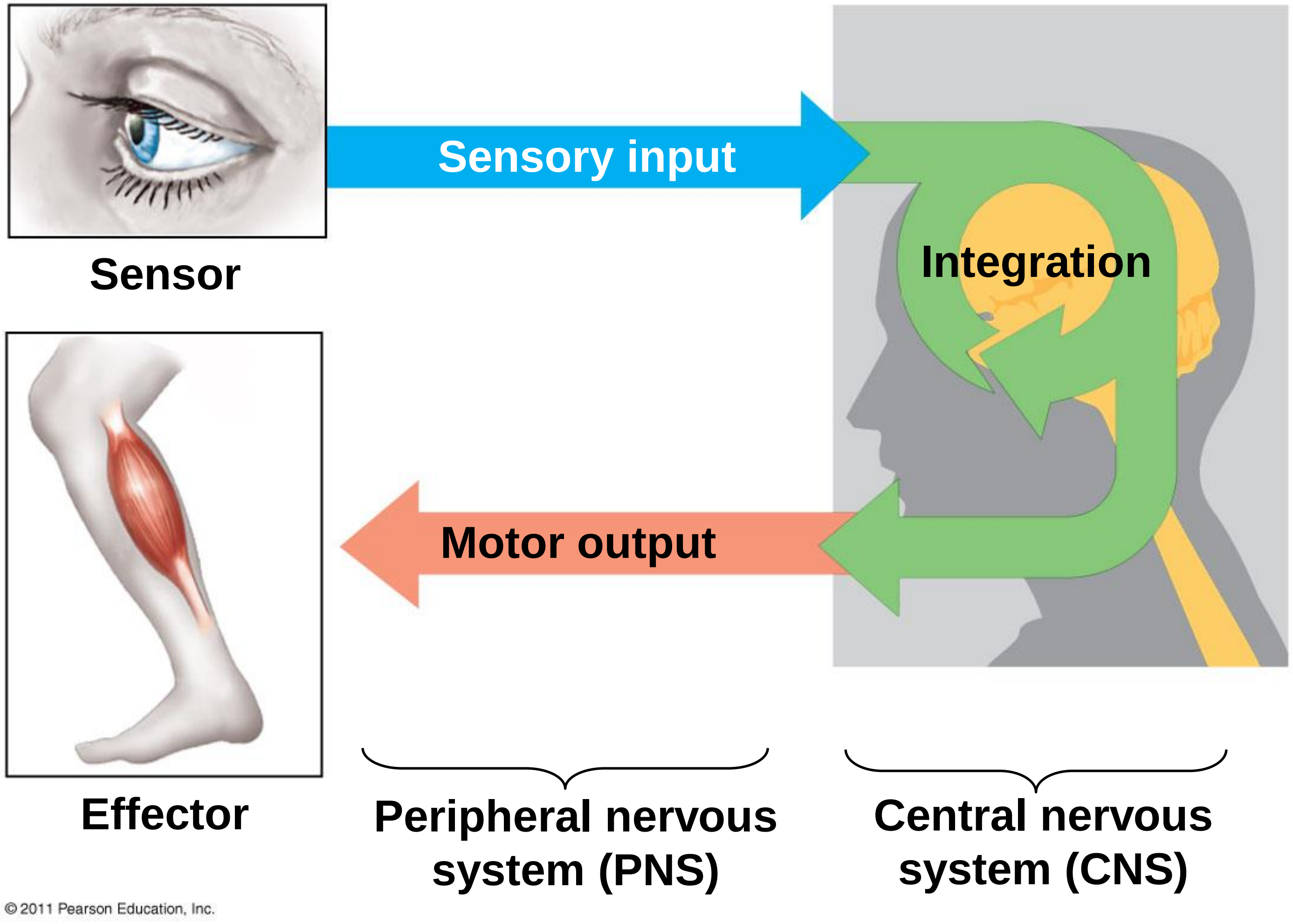
The Neuron

- The brain's unique information processing capabilities arise from its massively parallel and distributed way of computing.
- The workhorse of the brain is a type of cell known as a ***NEURON***.
- Neuron is a complex electrochemical device that receives information from hundreds of other neurons, processes this information, and conveys its output to hundreds of other neurons

The Neuron

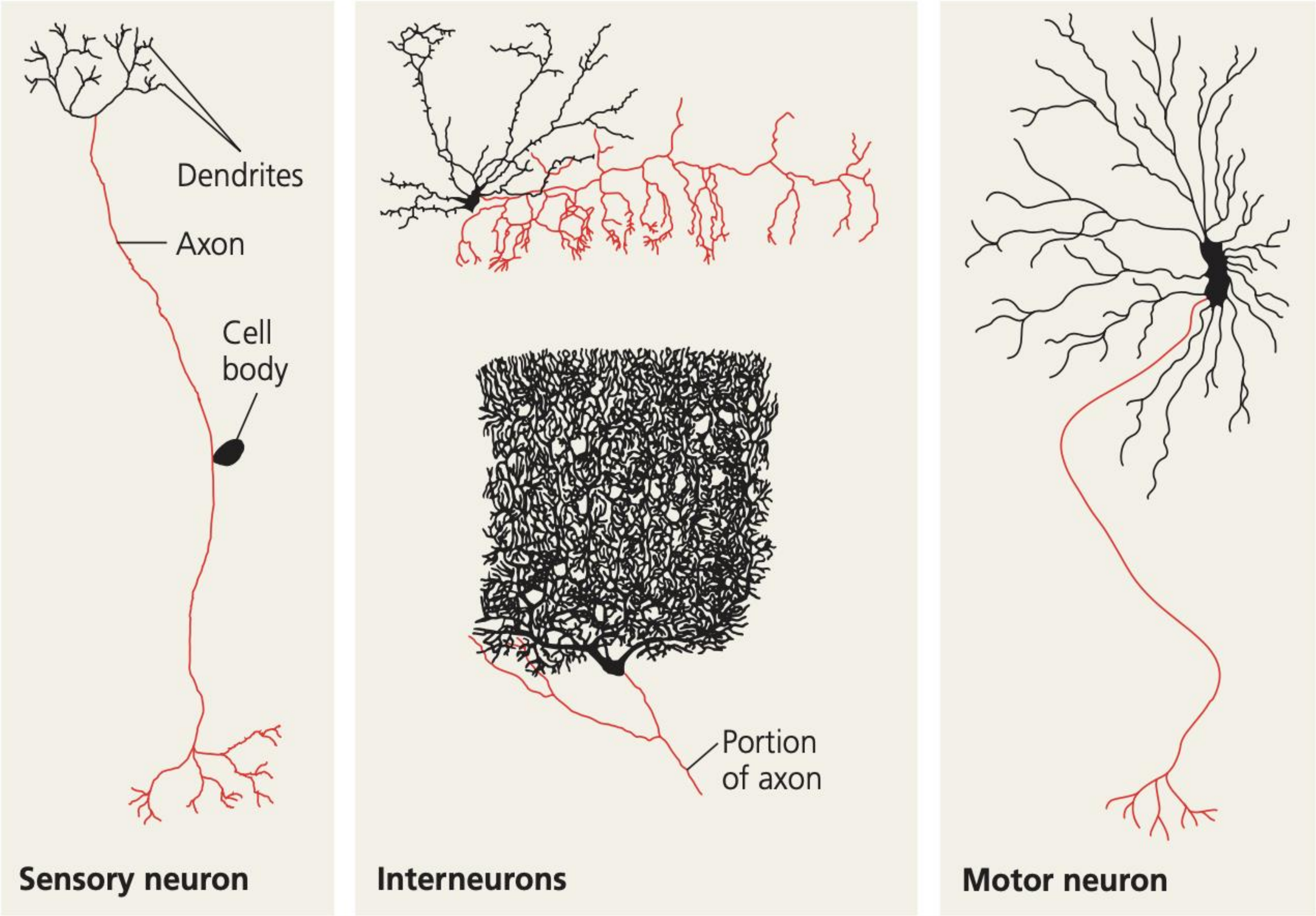
- The neuron can be regarded as a leaky bag of charged liquid.
- The membrane of a neuron is made up of a lipid bi-layer that is impermeable except for openings called ionic channel.
- The ionic channels selectively allow the passage of a few ions

REVISIT : Introduction to Information Processing



Many animals have a complex nervous system that consists of

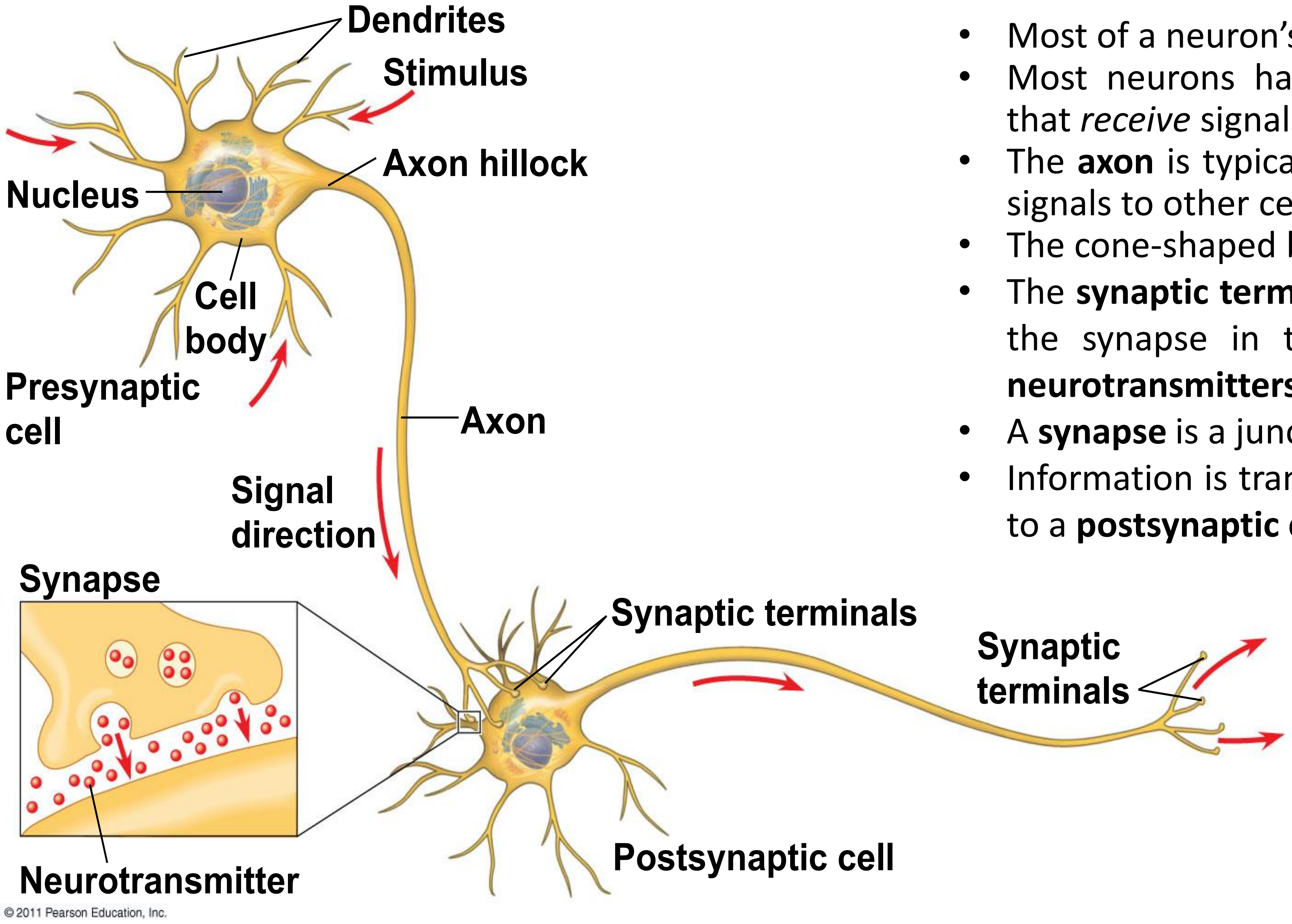
- A **central nervous system (CNS)** where integration takes place; this includes the brain and a nerve cord
- A **peripheral nervous system (PNS)**, which carries information into and out of the CNS
- The neurons of the PNS, when bundled together, form **nerves**



Structural diversity of neurons. Cell bodies and dendrites are black in these diagrams; axons are red. In the sensory neuron, unlike the other neurons here, the cell body is located partway along the axon that conveys signals from the dendrites to the axon's terminal branches.

- Sensors detect external stimuli and internal conditions and transmit information along **sensory neurons**
- Sensory information is sent to the brain, where **interneurons** integrate the information
- Motor output leaves the brain via **motor neurons**, which trigger muscle or gland activity

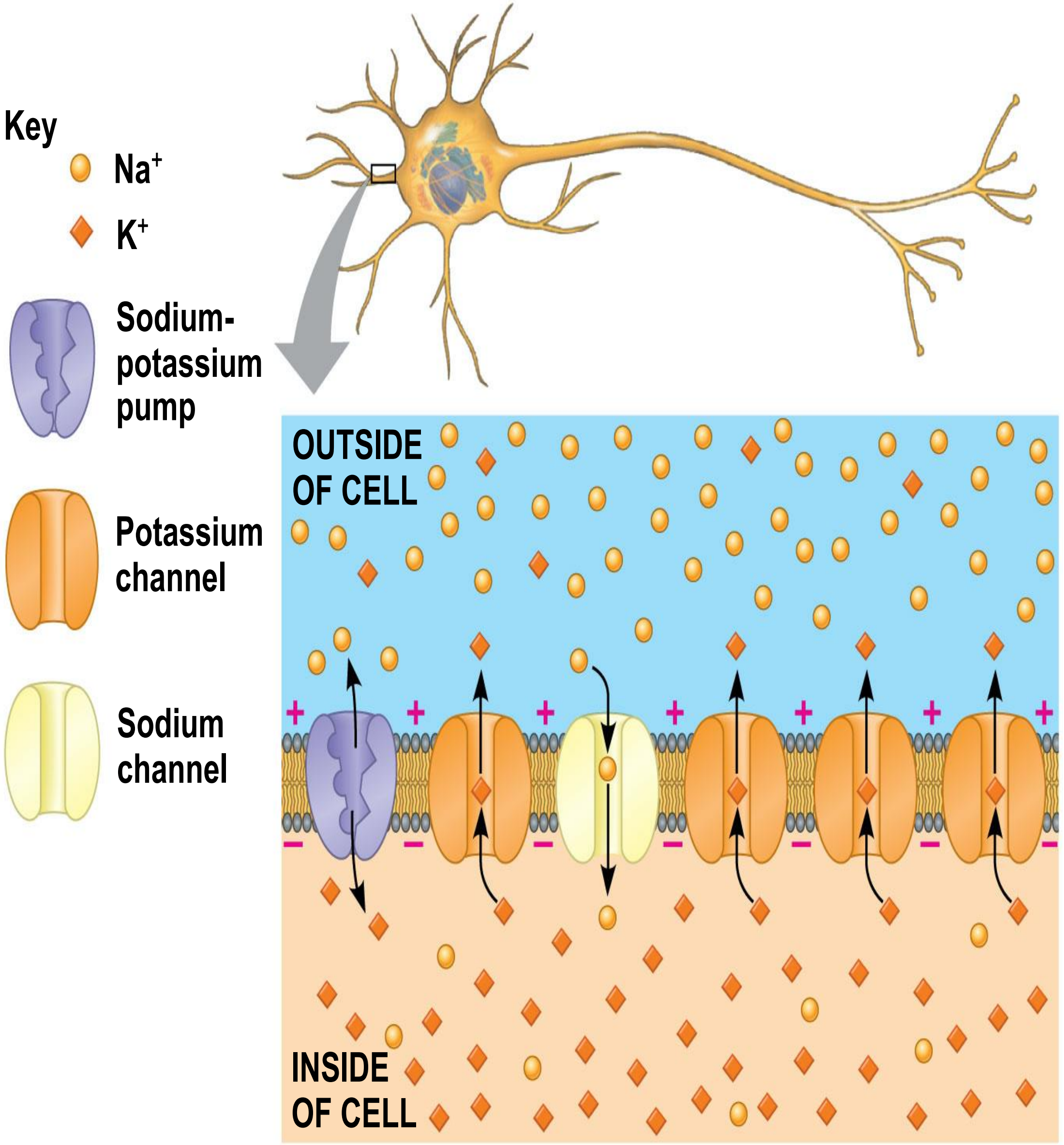
Neuron Structure and Function



- Most of a neuron's organelles are in the **cell body.**
- Most neurons have **dendrites**, highly branched extensions that *receive* signals from other neurons.
- The **axon** is typically a much longer extension that transmits signals to other cells at synapses.
- The cone-shaped base of an axon is called the **axon hillock.**
- The **synaptic terminal** of one axon passes information across the synapse in the form of chemical messengers called **neurotransmitters.**
- A **synapse** is a junction between an axon and another cell
- Information is transmitted from a **presynaptic cell** (a neuron) to a **postsynaptic cell** (a neuron, muscle, or gland cell).

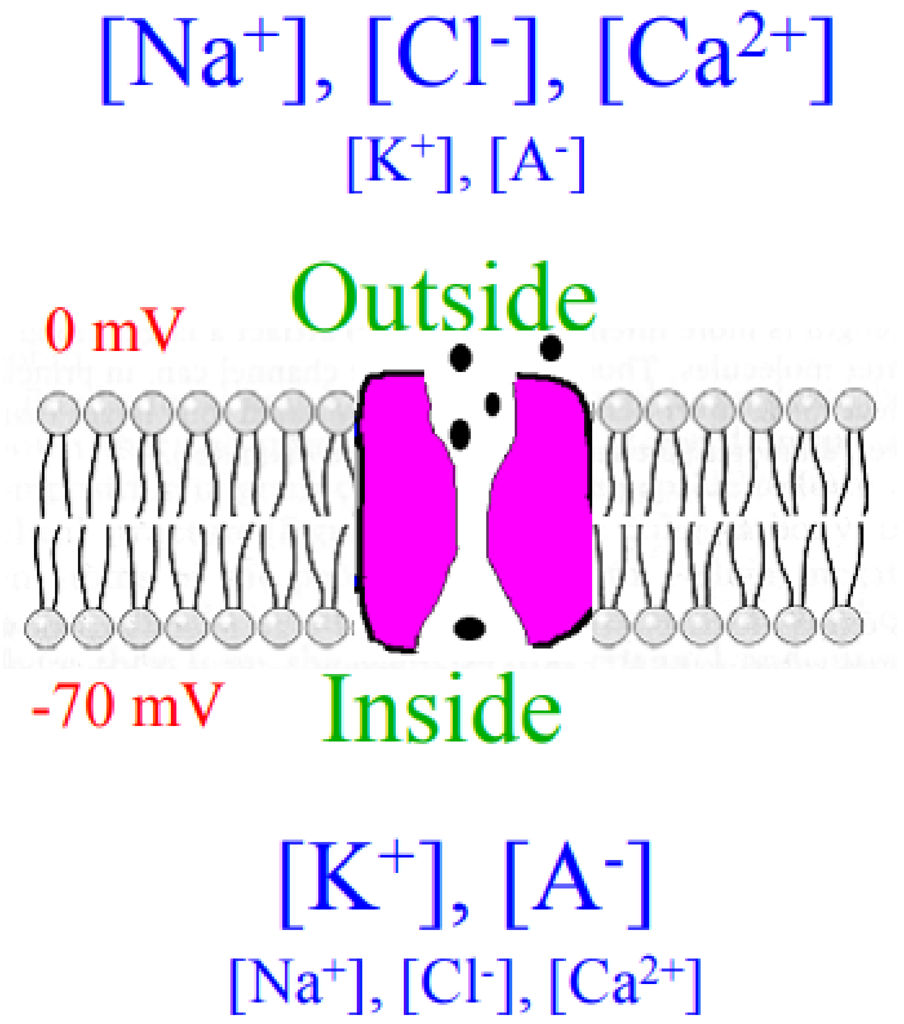
Ion pumps and ion channels establish the resting potential of a neuron

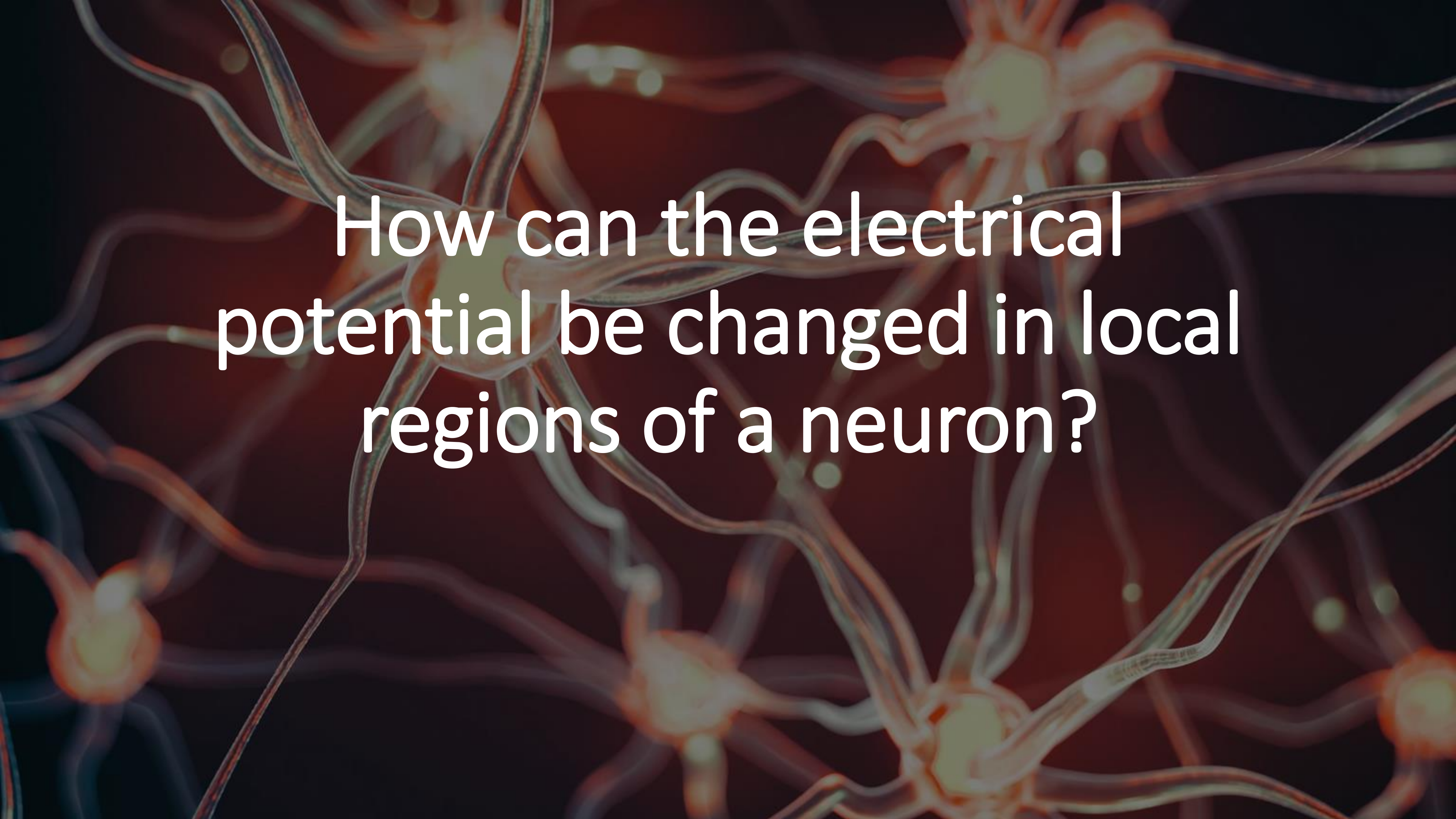
- Every cell has a voltage (difference in electrical charge) across its plasma membrane called a **membrane potential.**
- The **resting potential** is the membrane potential of a neuron not sending signals.
- Changes in membrane potential act as signals, transmitting and processing information.
- In a mammalian neuron at resting potential, the concentration of K^+ is highest inside the cell, while the concentration of Na^+ is highest outside the cell.
- The opening of **ion channels** in the plasma membrane converts chemical potential to electrical potential.
- A neuron at resting potential contains many open K^+ channels and fewer open Na^+ channels; K^+ diffuses out of the cell.
- The resulting buildup of negative charge within the neuron is the major source of membrane potential.



The Electrical Personality of a Neuron

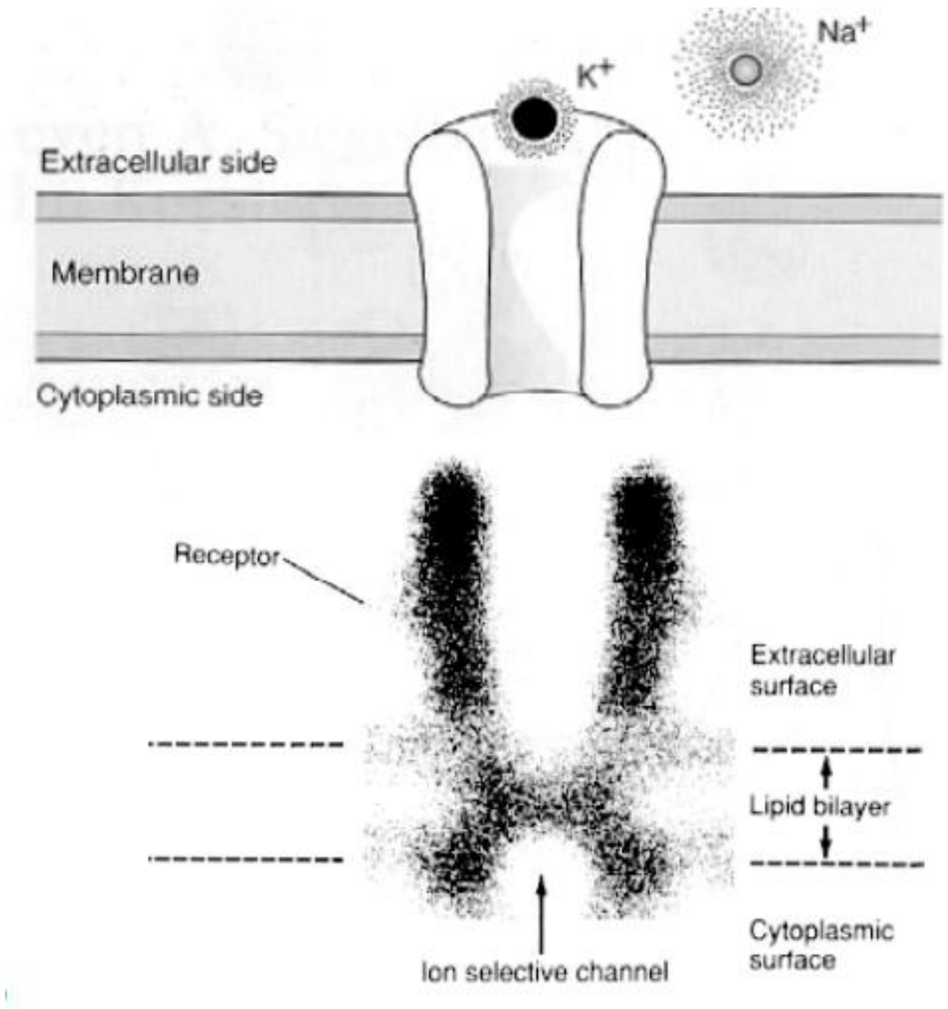
- Each neuron maintains a potential difference across its membrane
- Inside is ±70 to ±80 mV relative to outside
- [Na+], [Cl-] and [Ca2+] higher outside; [K+] and organic anions [A-] higher inside
- Ionic pump maintains -70 mV difference by expelling Na+ out and allowing K+ ions in




How can the electrical potential be changed in local regions of a neuron?

Ionic Channels: The Gatekeepers

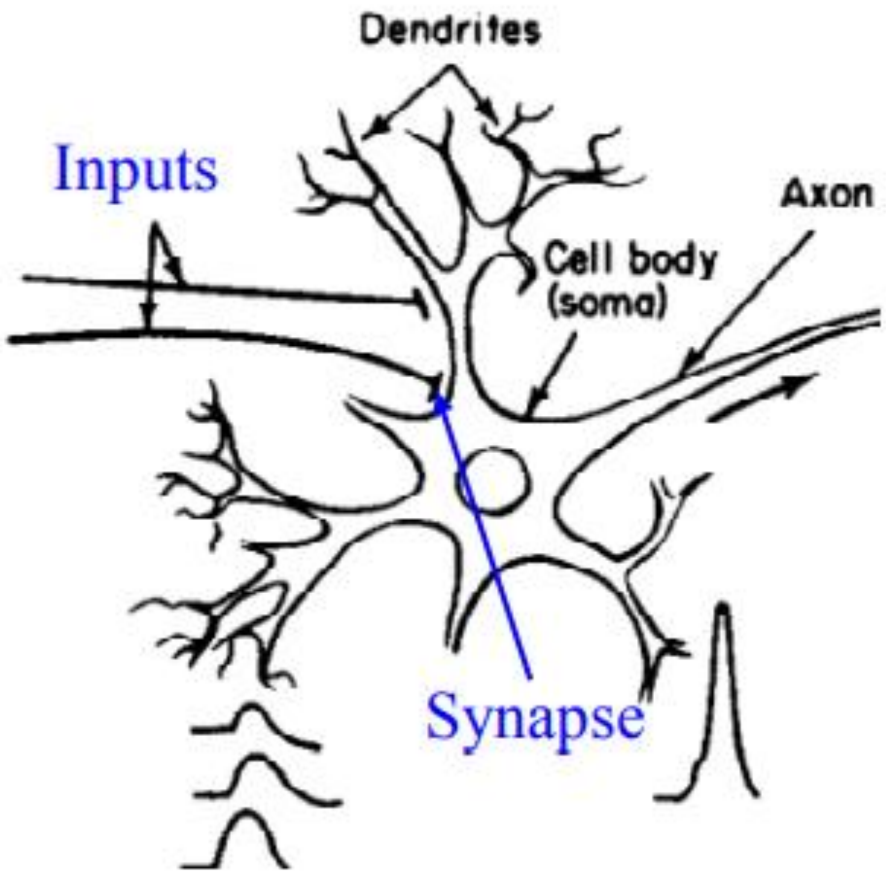
- Proteins in membranes act as channels that allow specific ions to pass through.
  - E.g.: Pass K+ but not Cl- or Na+
- These **IONIC CHANNELS** are gated
  - Voltage-gated: Probability of opening depends on membrane voltage
  - Chemically-gated: Binding to a chemical causes channel to open
  - Mechanically-gated: Sensitive to pressure or stretch



From Kandel, Schwartz, Jessel, Principles of Neural Science, 3rd edn., 1991, pgs. 68 & 137

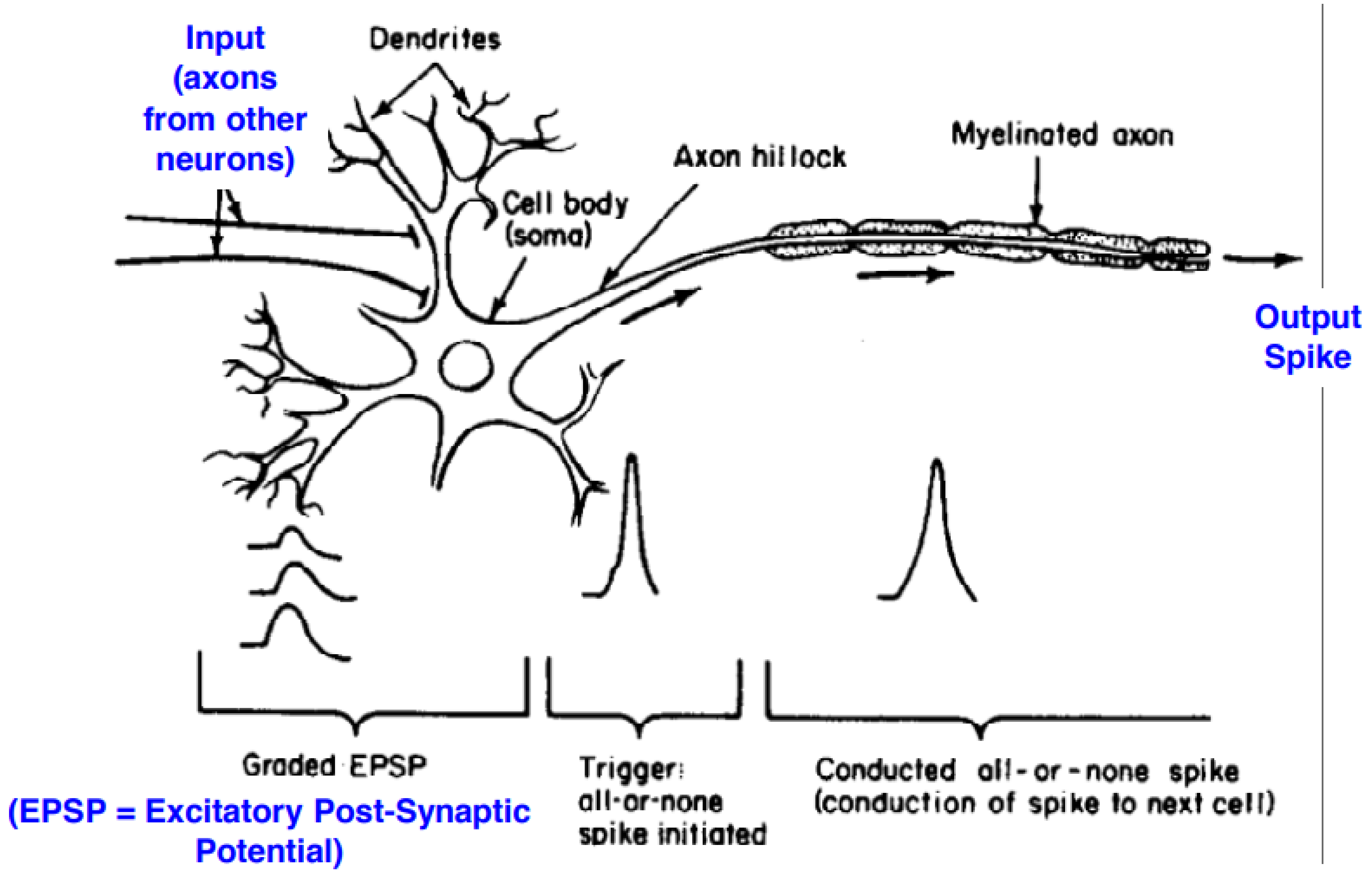
Gated Channels allow Neuronal Signaling

- Inputs from other neurons -> chemically-gated channels (at “synapses”) -> Changes in local membrane potential
- This causes opening/closing of voltage-gated channels in dendrites, body, and axon, resulting in depolarization (positive change in voltage) or hyperpolarization (negative change)



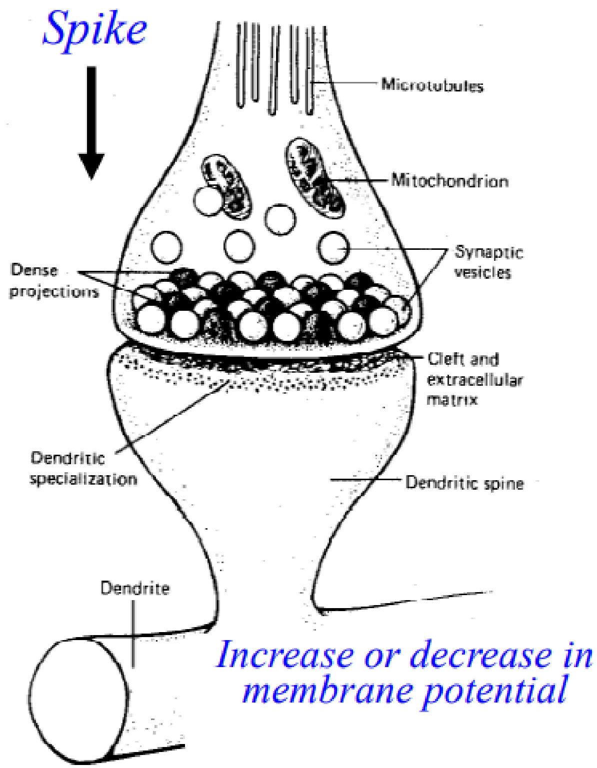
Regions of Neurons

- Neurons in different regions of the brain have different morphological structures
- The typical structure includes a cell body (called the soma) connected to a tree-like structure with branches called dendrites
- A single branch called the axon that emanates from the soma and conveys the output spike to other neurons.
- The spike is typically initiated near the junction of the soma and axon and propagates down the length of the axon.
- Many axons are covered by myelin, a white sheath that significantly boosts the speed of propagation of the spike over long distances.


Input
(axons
from other
neurons)
Dendrites
Cell body
(soma)
Axon hillock
Myelinated axon
Output
Spike
Graded EPSP
(EPSP = Excitatory Post-Synaptic
Potential)
Trigger:
all-or-none
spike initiated
Conducted all-or-none spike
(conduction of spike to next cell)

Synapse

- Neurons communicate with each other through connections known as synapses.
- Synapses can be electrical but are more typically chemical.
- A synapse is essentially a gap or cleft between the axon of one neuron (called the presynaptic neuron) and a dendrite (or soma) of another neuron (called the postsynaptic neuron)



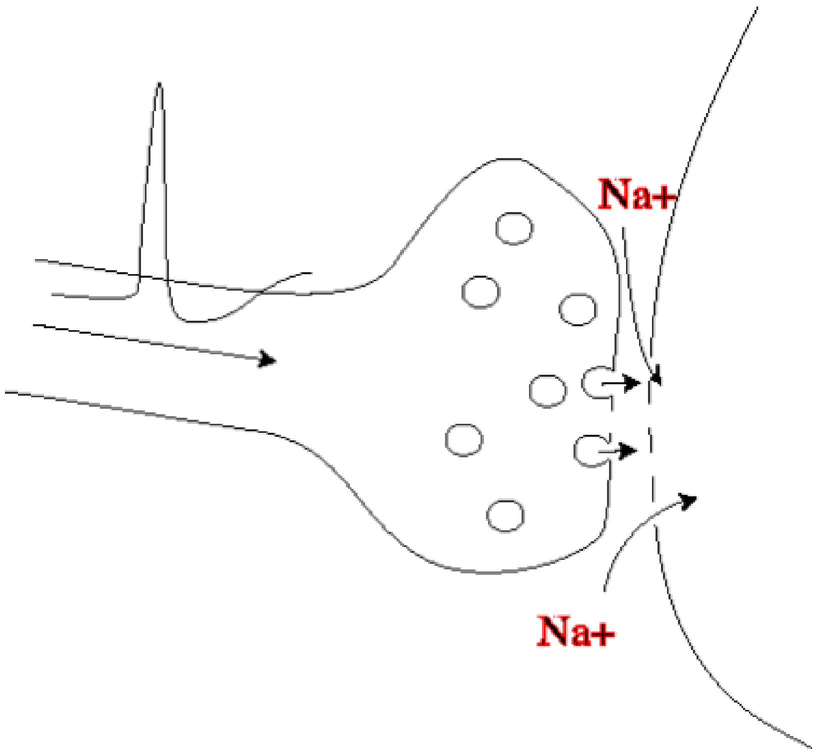
Synapse

- When an action potential arrives from a presynaptic neuron, it causes the release of chemicals known as neurotransmitters into the synaptic cleft.
- These chemicals in turn bind to the ionic channels (or receptors) on the postsynaptic neuron, causing these *channels to open*, thereby influencing the local membrane potential of the postsynaptic cell.

Synapse

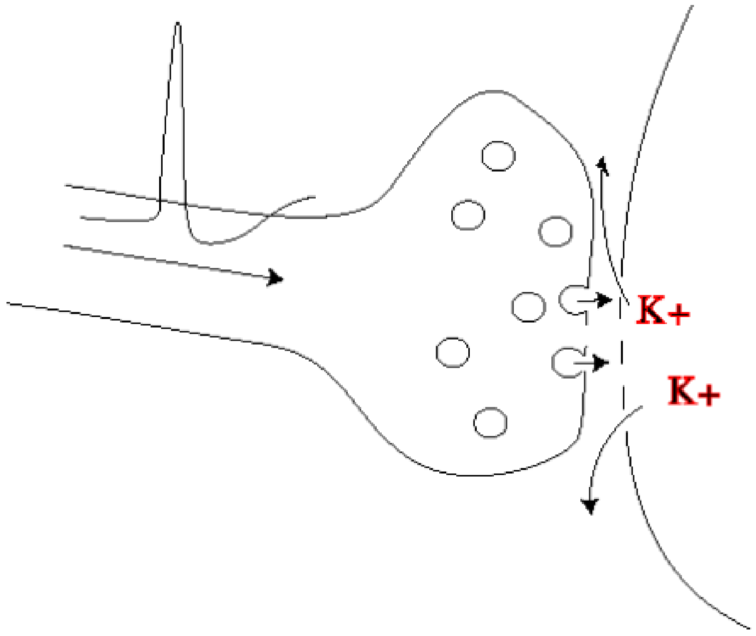
- Synapses can be excitatory or inhibitory.
- Excitatory synapses cause a momentary increase in the local membrane potential of the postsynaptic cell.
  - This increase is called an excitatory postsynaptic potential (EPSP).
  - EPSPs contribute to a higher probability of firing a spike by the postsynaptic cell.
- Inhibitory synapses do the opposite, temporarily decrease the local membrane potential of the postsynaptic cell
  - They cause inhibitory postsynaptic potentials (IPSPs)
- A neuron is called excitatory or inhibitory based on the kind of synapse it forms with *postsynaptic neurons*

An Excitatory Synapse



Input spike → Neurotransmitter release → Binds to Na channels (which open) → Na+ influx → Depolarization due to EPSP (excitatory postsynaptic potential)

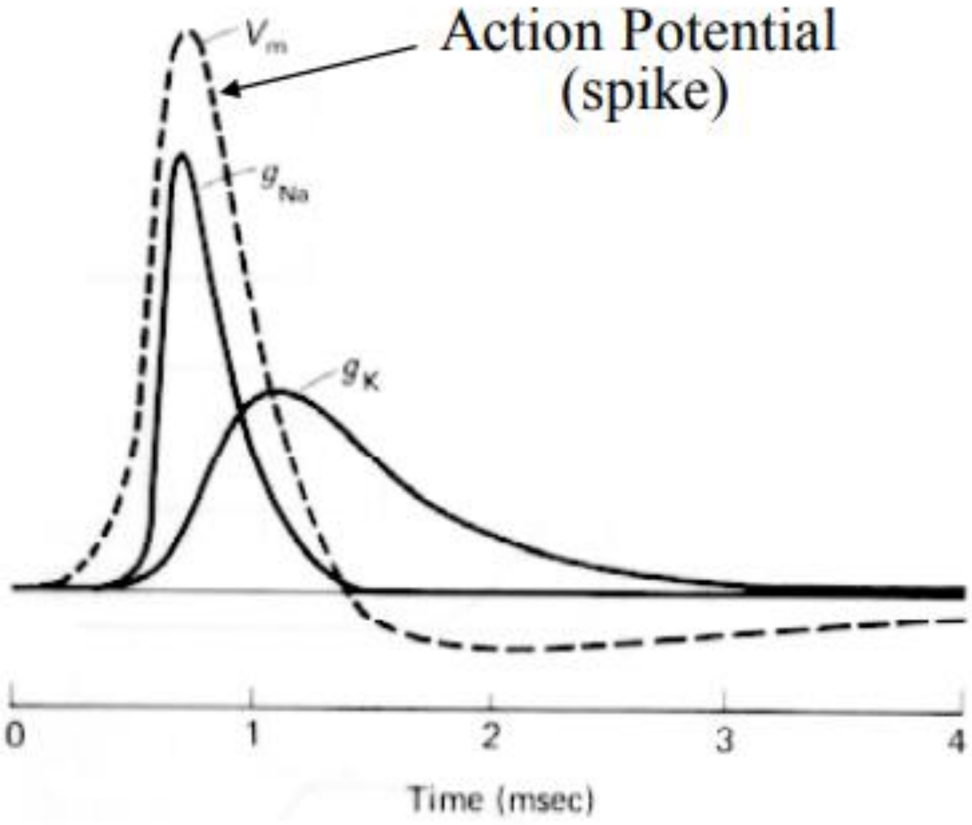
An Inhibitory Synapse



Input spike → Neurotransmitter release → Binds to K channels → K+ leaves cell → Hyperpolarization due to IPSP (inhibitory postsynaptic potential)

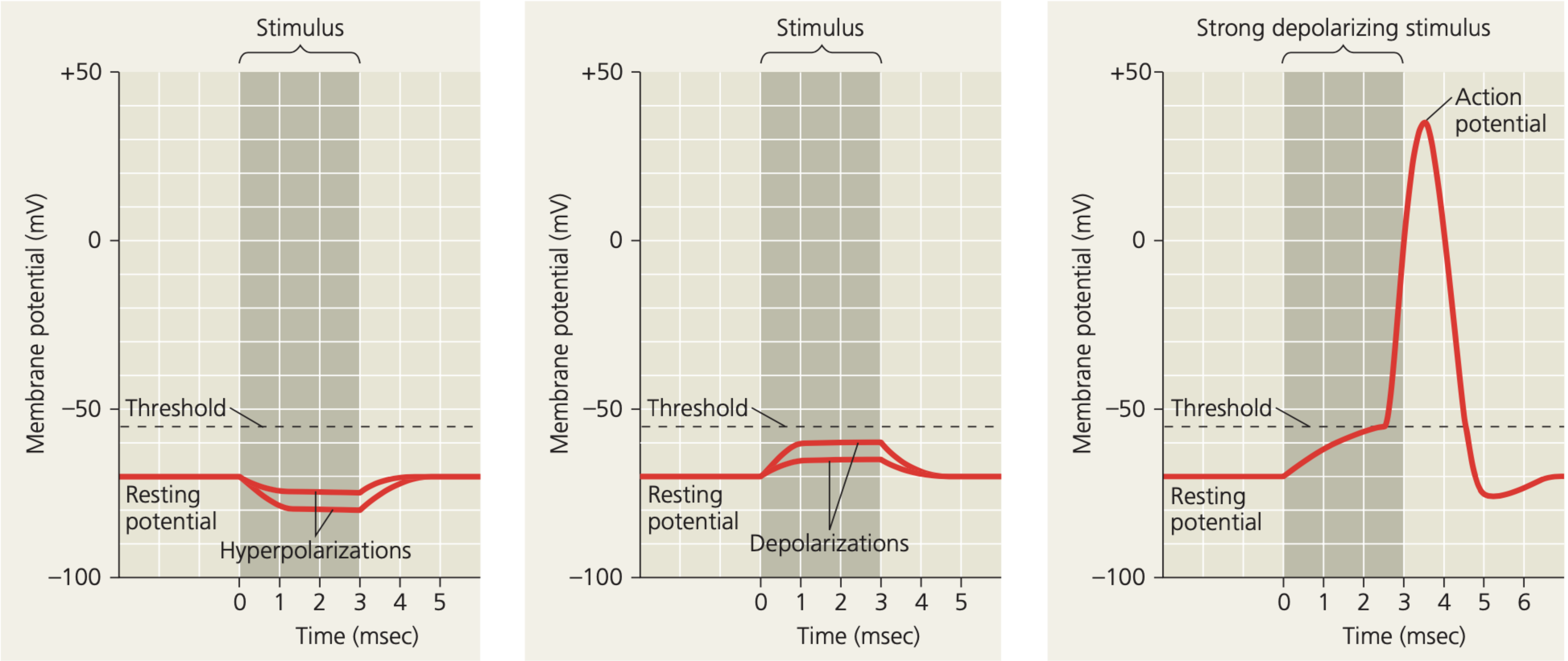
Action Potential or Spikes

- When the neuron receives sufficiently strong inputs from other neurons a cascade of events is triggered
- Rapid influx of Na+ ions into the cell
  - *Causing the membrane potential to rise rapidly.*
- The opening of K+ channels triggers the outflux of K+ ions
  - *Causing a drop in the membrane potential.*
- This rapid rise and fall of the membrane potential is called an ***action potential*** or **spike** and represents the dominant mode of communication between one neuron and another.



From Kandel, Schwartz, Jessel, Principles of Neural Science, 3rd edn., 1991, pg. 110

Graded potentials and an action potential in a neuron.



(a) Graded hyperpolarizations produced by two stimuli that increase membrane permeability to K^+. The larger stimulus produces a larger hyperpolarization.

(b) Graded depolarizations produced by two stimuli that increase membrane permeability to Na^+. The larger stimulus produces a larger depolarization.

(c) Action potential triggered by a depolarization that reaches the threshold.

Spike Generation

- The generation of a spike by a neuron involves a complex cascade of events involving sodium and potassium channels
- This process can be simplified into a simple threshold model of spike generation.
  - *When the neuron receives sufficiently strong inputs from its synapses for its membrane potential to cross a neuron-specific threshold, a spike is emitted.*

Synaptic plasticity: Adapting the connections

- **Long Term Potentiation (LTP):** Increase in synaptic strength of a synaptic connection between two neurons caused by correlated firing of the two neurons
  - lasts for several hours or more.
- Measured as an increase in the excitatory postsynaptic potential (EPSP) caused by presynaptic spikes
- LTP has been found in several brain areas including the hippocampus and the neocortex.
- Note: *LTP is regarded as a biological implementation of Donald Hebb's famous postulate (also called Hebbian learning or Hebbian plasticity) that if a neuron A is consistently involved in causing another neuron B to fire, then the strength of the connection from A to B should be increased.*

Synaptic plasticity: Adapting the connections

- **<u>Long-term depression or LTD:</u>** Decrease in the strength of a synaptic connection caused
  - by uncorrelated firing between the two neurons involved.
  - Reduction in synaptic strength that lasts for several hours or more
- LTD has been observed most prominently in the cerebellum, although it also coexists with LTP in the hippocampus, neocortex, and other brain areas

Synaptic plasticity: Adapting the connections

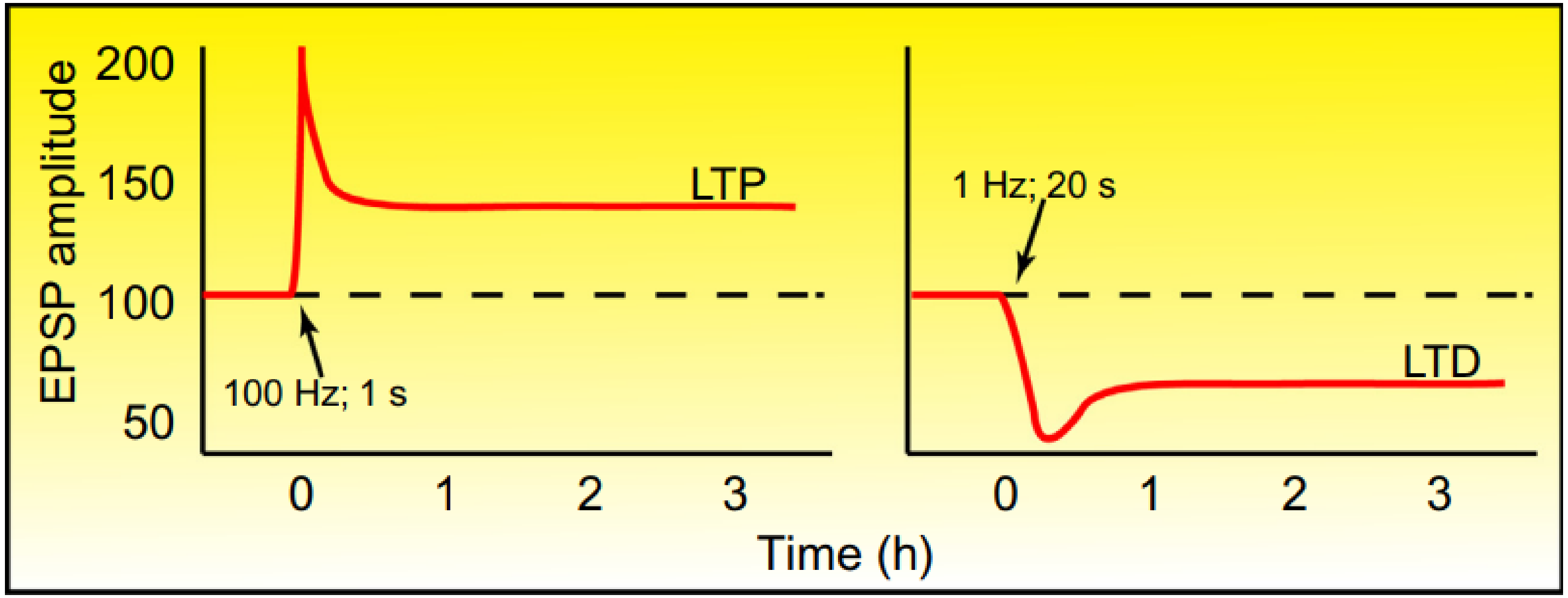


Figure: Long-term potentiation (LTP) and long-term depression (LTD).
Plots of excitatory postsynaptic potential amplitude at a hippocampal synapse over time during two different stimulus patterns. (Left panel) Following a long burst of high-frequency stimulation (100 Hz for 1 s), synapses strengthen, leading to a larger EPSP amplitude, and this is maintained for hours (LTP). The transient spike in strengthening that occurs immediately after the 100 Hz stimulus train results from post-tetanic potentiation. (Right panel) Following a low-frequency train of activity (1 Hz for 20 s), synapses weaken persistently, leading to a smaller EPSP amplitude (LTD).

Image from: *Meriney, Stephen D. (2019). Synaptic Transmission || Synaptic Plasticity. , (), 287–329.*

Synaptic plasticity: Adapting the connections

- **<u>Spike timing dependent plasticity (STDP):</u>**
  - The relative timing of input and output spikes determines the polarity of synaptic change.
- The timing between presynaptic and postsynaptic spikes
  - Can determine whether the change in synaptic strength is positive or negative
- ***Hebbian STDP***: If the presynaptic spike occurs slightly before the postsynaptic spike (e.g., 1–40 ms before), the synapse is strengthened, whereas if the presynaptic spike occurs slightly after (e.g., 1–40 ms after), the synaptic strength is decreased.

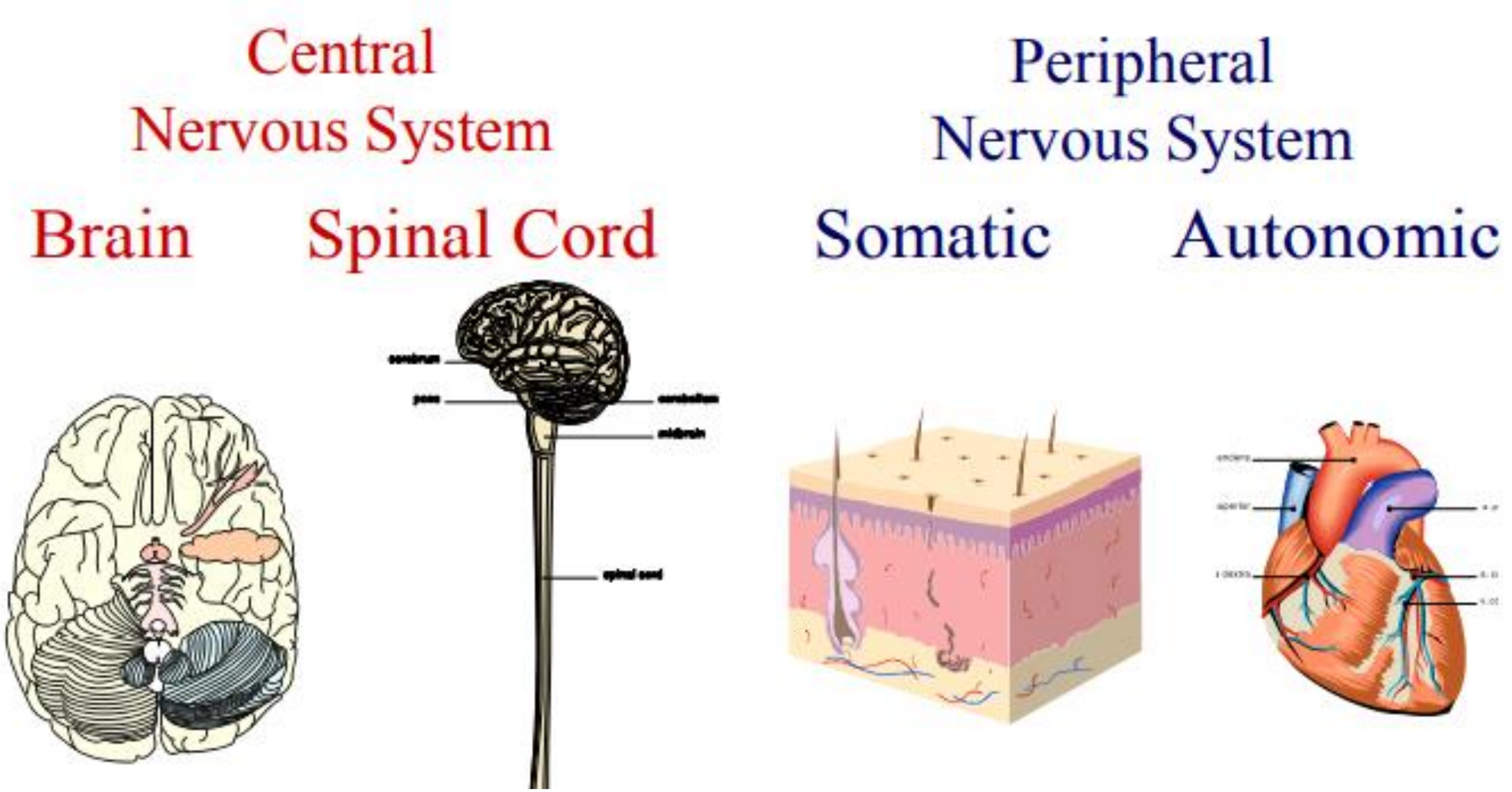
Synaptic plasticity: Adapting the connections

- Short-term facilitation/depression
  - The plasticity is rapid but not long-lasting.
- Short-term depression: The effect of each successive spike in an input spike train (sequence of spikes) is diminished compared to the preceding spike.
- Short-term facilitation: The effect of each successive spike has a larger effect than its predecessor, until a saturation point is reached

Brain Organization, Anatomy, and Function

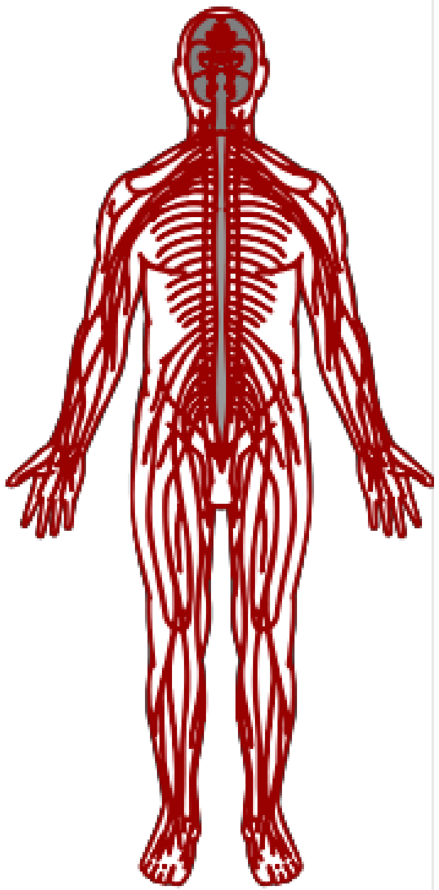
- The design of a brain-computer interface typically involves choices regarding which brain areas to record from and, in some cases, which brain areas to stimulate.
- The human nervous system can be broadly divided into
  - The central nervous system (CNS).
    - The CNS consists of the brain and the spinal cord.
  - The peripheral nervous system (PNS).
    - The PNS consists of the somatic nervous system (neurons connected to skeletal muscles, skin, and sense organs) and the autonomic nervous system (neurons that control visceral functions such as the pumping of the heart, breathing, etc.).

Brain Organization, Anatomy, and Function



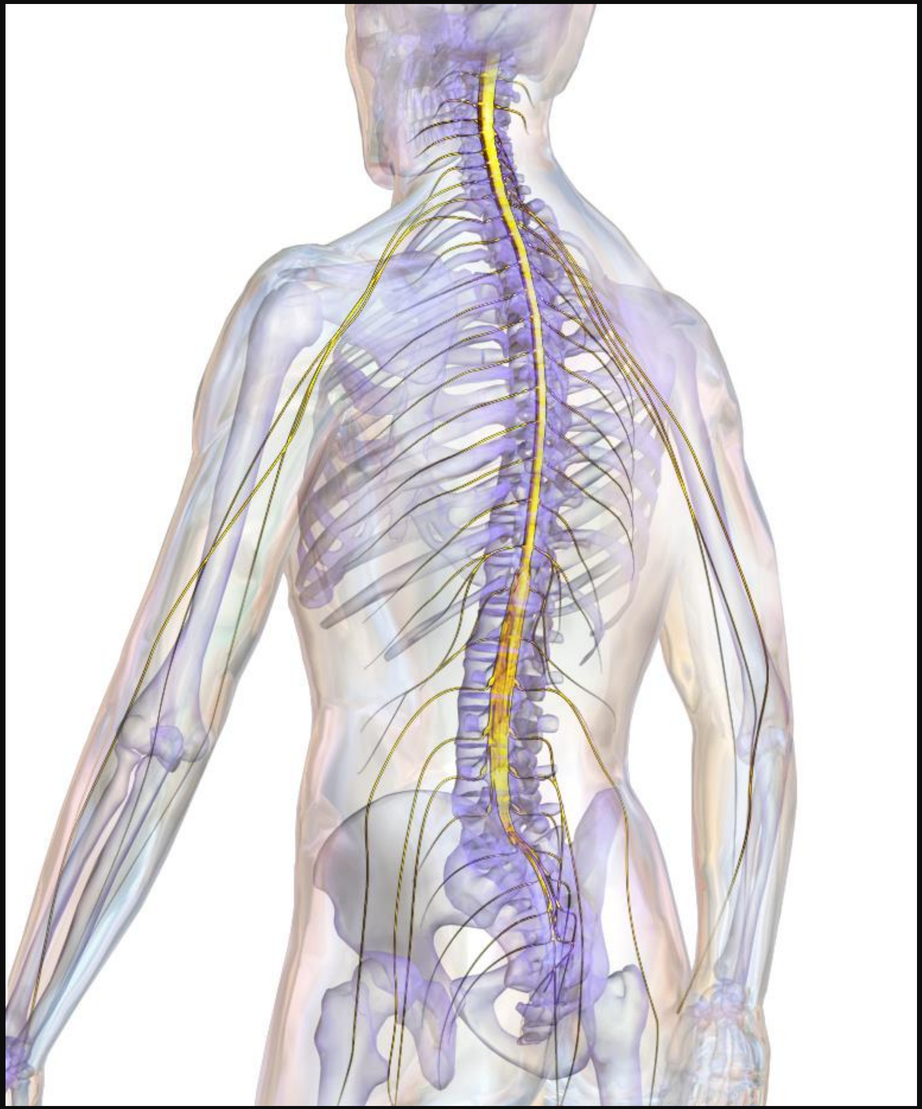
Skeletal/Somatic Nervous System

- Nerves that connect to voluntary skeletal muscles and to sensory receptors
- Afferent Nerve Fibers (incoming)
  - Axons that carry info away from the periphery to the CNS
- Efferent Nerve Fibers (outgoing)
  - Axons that carry info from the CNS outward to the periphery



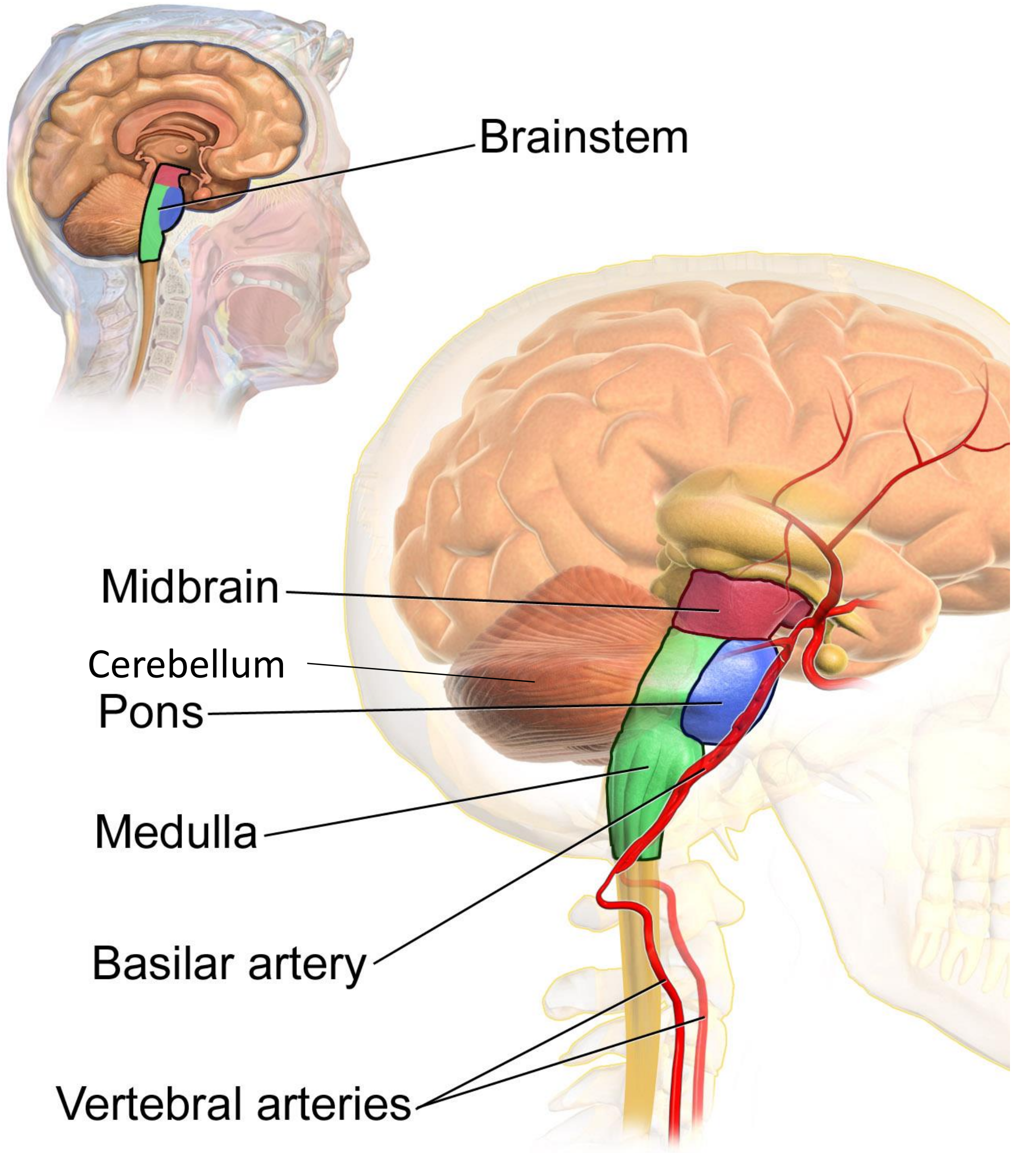
Autonomic and Central Nervous System

- Autonomic: Nerves that connect to the heart, blood vessels, smooth muscles, and glands
- CNS = Brain + Spinal Cord
- Spinal Cord
  - Local feedback loops control reflexes
  - Descending motor control signals from the brain activate spinal motor neurons
  - Ascending sensory axons transmit sensory feedback information from muscles and skin back to brain



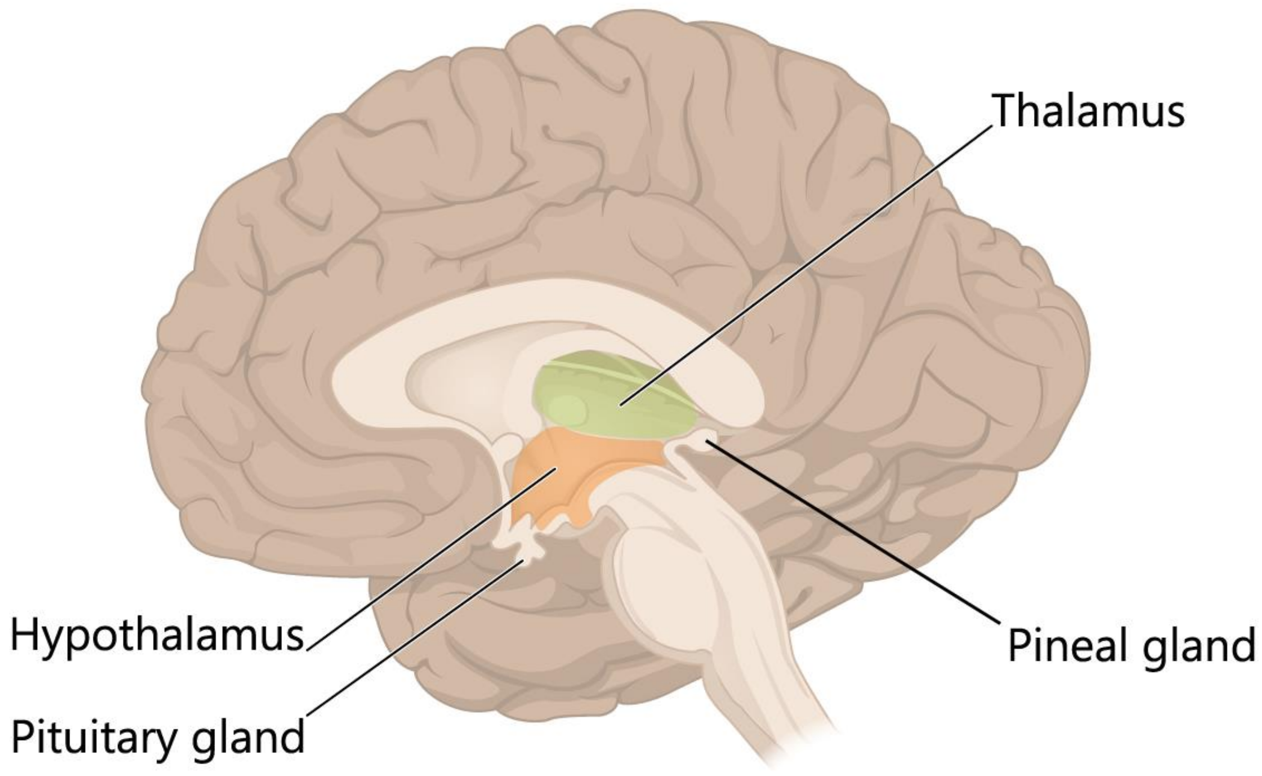
Major Brain Regions: Brain Stem

- Medulla: Breathing, muscle tone and blood pressure
- Pons: Connects brainstem with cerebellum & involved in sleep and arousal
- Cerebellum: Coordination of voluntary movements and sense of equilibrium
- Midbrain: Eye movements, visual and auditory reflexes



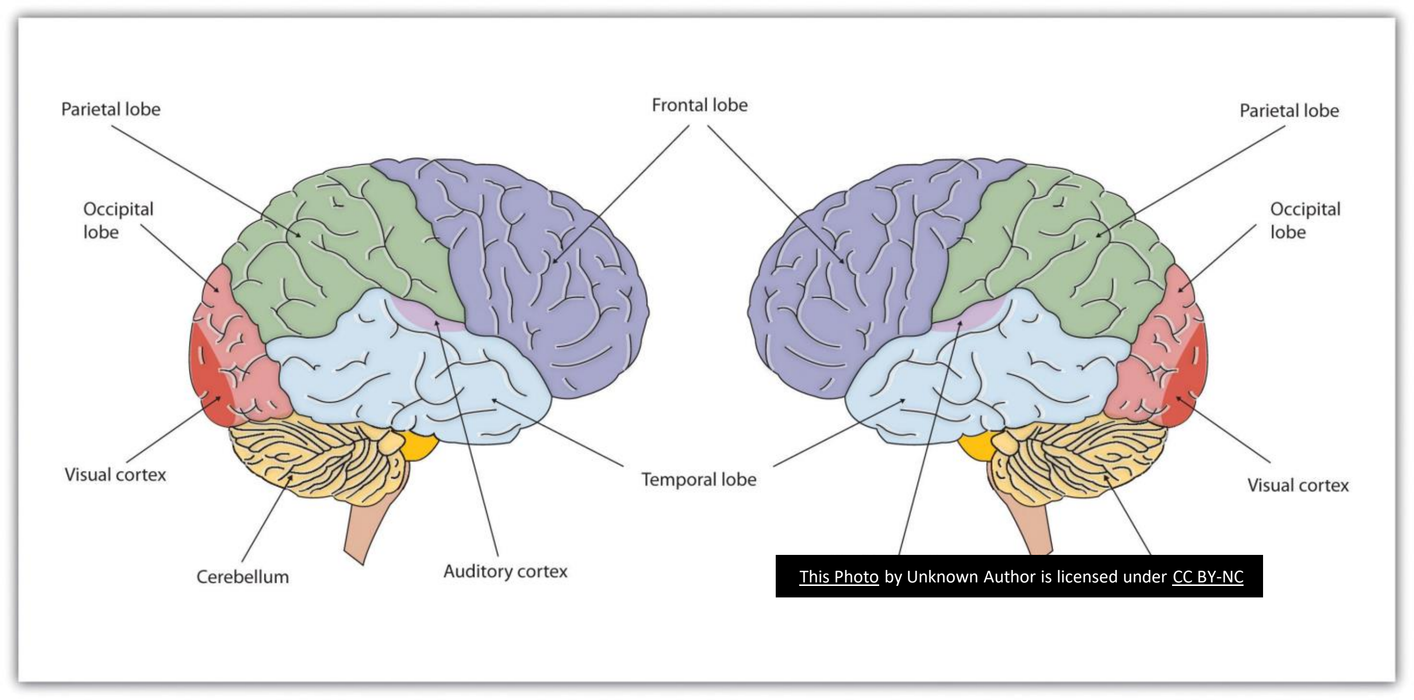
Major Brain Regions: Diencephalon

- Thalamus: Relay station for all sensory info (except smell) to the cortex
- Hypothalamus Regulates basic needs fighting, fleeing, feeding, and mating



Major Brain Regions: Cerebral Hemispheres

- Consists of Cerebral cortex, basal ganglia, hippocampus, and amygdala
- Involved in perception and motor control, cognitive functions, emotion, memory, and learning



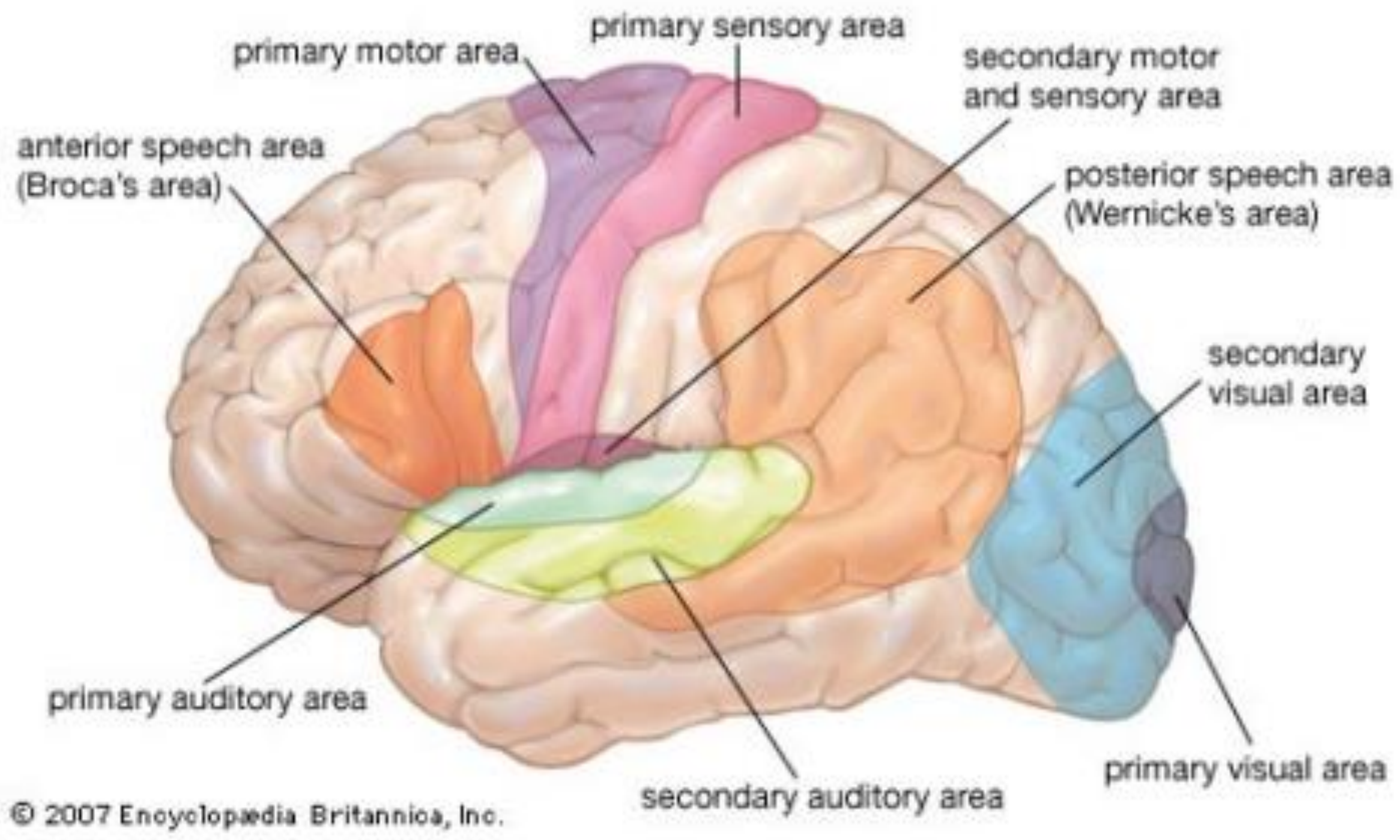


Figure 2.2: Regions of the cerebral cortex [Goldberg, 2002]

Cortical area	Function
Auditory association area	Complex processing of auditory information
Auditory cortex	Detection of sound quality (loudness, tone)
Broca's area (speech center)	Speech production and articulation
Prefrontal cortex	Problem solving, emotion, complex thought
Premotor cortex	Coordination of complex movement
Primary Motor cortex	Initiation of voluntary movement
Primary somatosensory cortex	Receives tactile information from the body
Sensory association area	Processing of multisensory information
Gustatory area	Processing of taste information
Wernicke's area	Language comprehension
Primary Visual Cortex	Complex processing of visual information

Brain Signal Acquisition

Course S2022

Faculty: Dr Annushree Bablani

Background

- The brain communicates using spikes-- produced when the neuron receives enough input current from other neurons via synaptic connections.

- Recording brain activity are based on detecting changes in electrical potentials in neurons
  - invasive techniques based on implanting electrodes

- Or on detecting changes in large populations of neurons
  - noninvasive techniques such as electroencephalography or EEG

Recording signals from brain

Invasive Approaches:

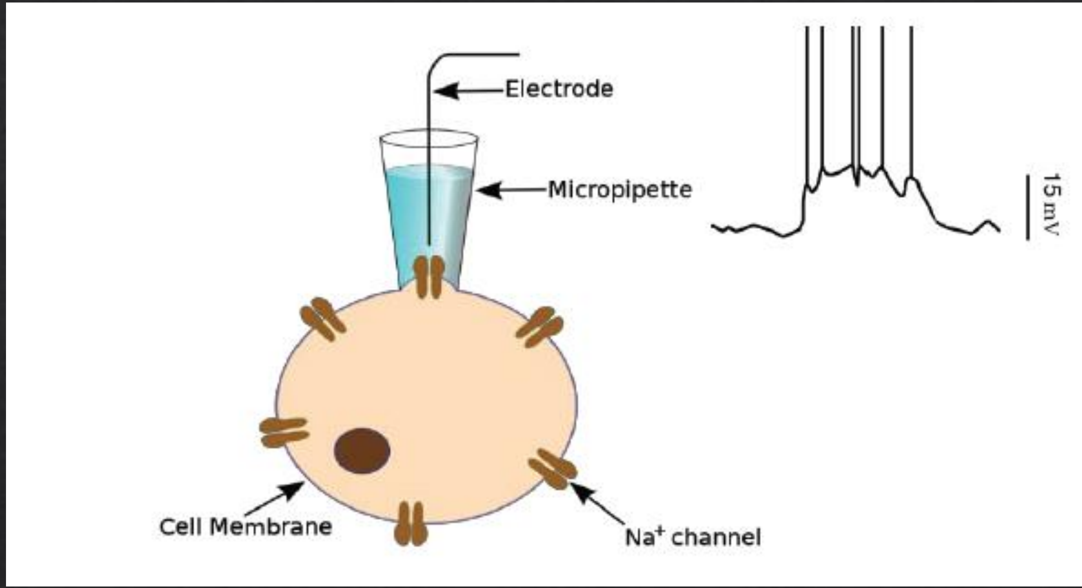
- Techniques that allow recording from individual neurons in the brain are typically invasive.
- They involve some form of surgery,
  - A part of the skull is removed, an electrode or implant placed in the brain, and the removed part of the skull then replaced.
- A major advantage of invasive recordings is that they allow recording of action potentials at the millisecond timescale.

Invasive Approaches

- **Microelectrodes:**
- A *microelectrode* is simply a very fine wire or other electrical conductor used to make contact with brain tissue.
- A typical electrode is made of tungsten or platinum- iridium alloy and is insulated except at the tip, which measures around 1µm in diameter (A neuron's cell body diameter is in the range of tens of µm).

Invasive Approaches

- **Intracellular Recording:**
- Measures the voltage or current across the membrane of the neuron.
- The most common technique, known as *patch clamp recording.*



- Very Delicate → Intracellular recordings are typically performed only on slices of brain tissue

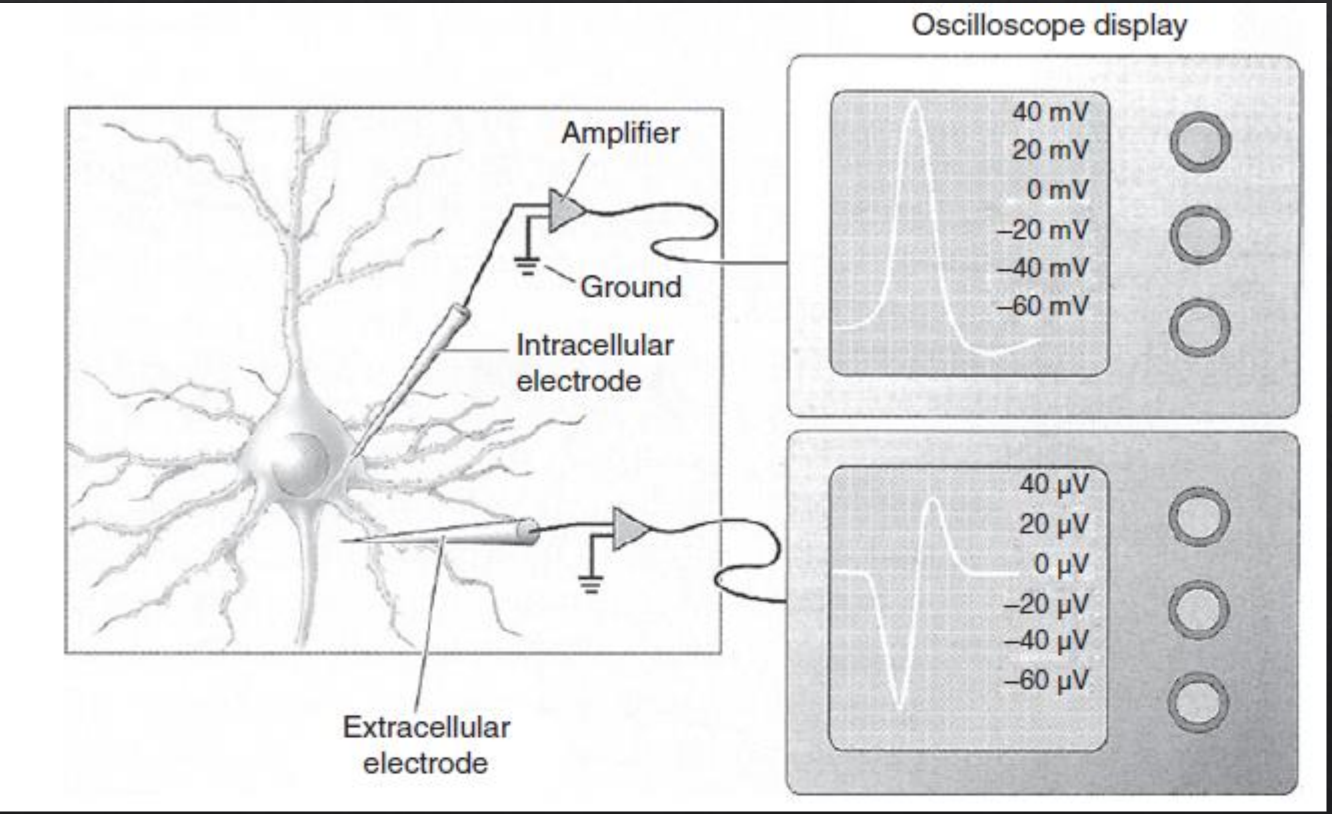
Invasive Approaches

- **Extracellular Recording:**
- Recording of a single neuron (or single“unit”): a tungsten or platinum-iridium microelectrode with a tip size of less than 10 microns is inserted into the target brain area.

- The magnitude of the recorded signal is usually less than a millivolt and thus requires the use of amplifiers to detect the signal.

- The signal from the amplifier is fed to a computer, which performs additional processing such as filtering noise and isolating the spikes (action potentials).

Invasive Approaches



(from Bear et al., 2007).

Invasive Approaches

- When the neuron produces a spike, positive ions flow away from the extracellular electrode into the neuron, causing the initial negative deflection in the display. This is followed by a positive deflection as the action potential decreases and positive charges flow out of the neuron toward the extracellular electrode.

Invasive Approaches

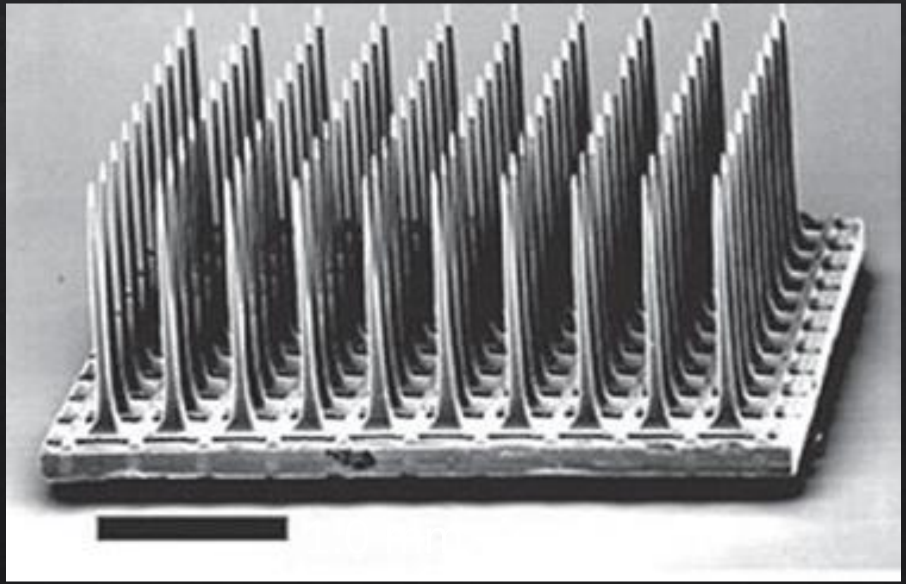
Tetrodes and Multi-Unit Recording:

- To record from multiple neurons simultaneously by using more than one electrode.
- Four wires are tightly wound together in a bundle.

Invasive Approaches

Multielectrode Arrays:

- To record from larger numbers of neurons, microelectrodes can be arranged in a grid-like structure to form a multielectrode array of $m \times n$ electrodes.



(adapted from Hochberg et al., 2006).

Invasive Approaches

- The most common types of implantable arrays are microwire, silicon-based, and flexible microelectrode arrays
- Increased spatial resolution
- The ability to record simultaneously from several dozens of neurons
- Opens the door to extracting complex types of information such as position or velocity signals that could be useful for controlling prosthetic devices.

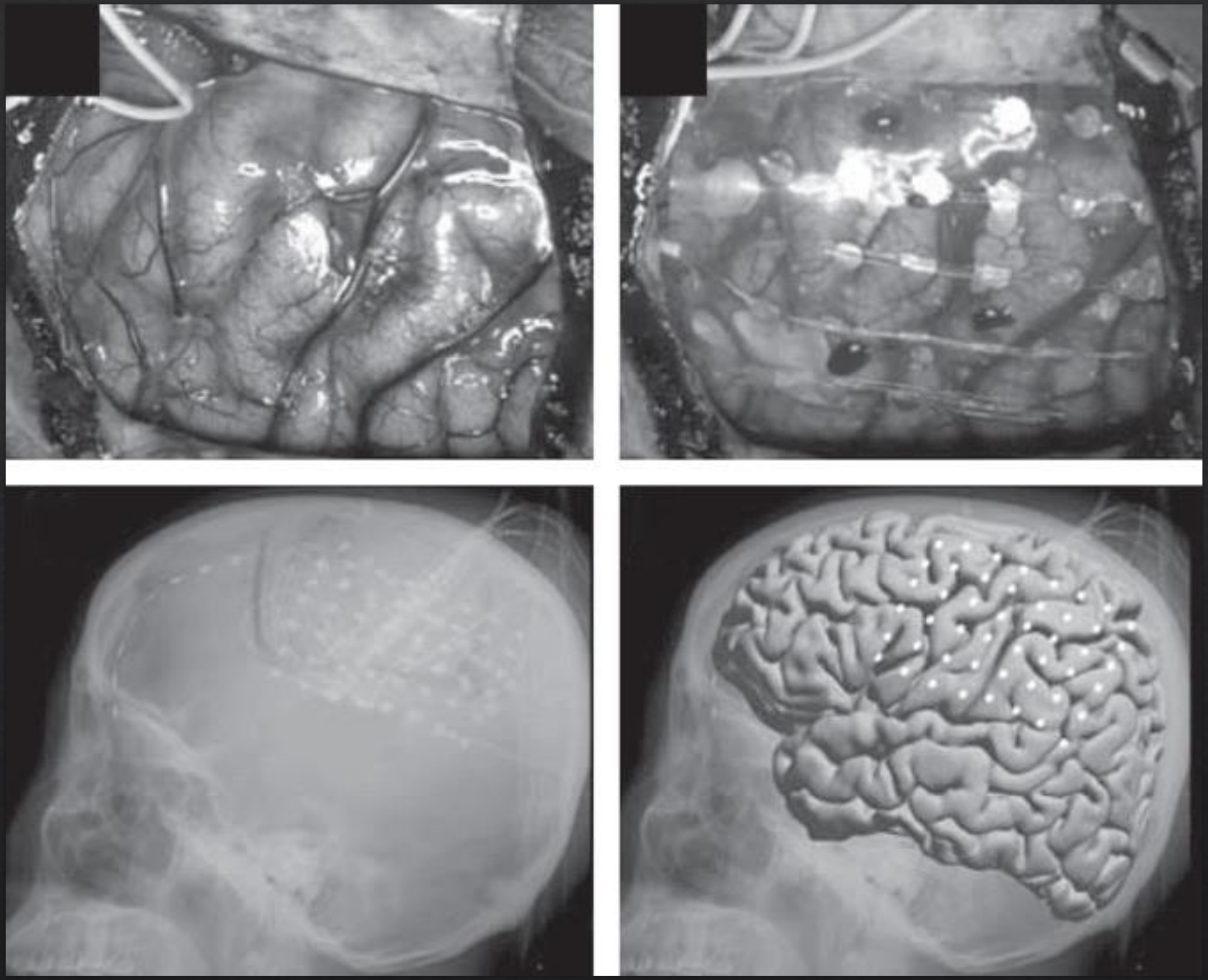
Partially Invasive Approach

Electrocorticography (ECoG):

- *Electrocorticography* (ECoG) is a technique for recording brain signals that involves placing electrodes on the surface of the brain.
- The procedure requires making a surgical incision into the skull to implant the electrodes on the brain surface

Partially Invasive Approach

- ECoG electrodes can record the electrical fluctuations caused by the coherent activity of large populations of neurons (several tens of thousands).
- Safer than arrays implanted inside the brain.
- ECoG electrodes may also be less likely to wear out compared to brain penetrating electrodes
- ECoG offers greater spatial resolution



(from (Miller et al., 2007).

Partially Invasive Approach

MicroECoG:

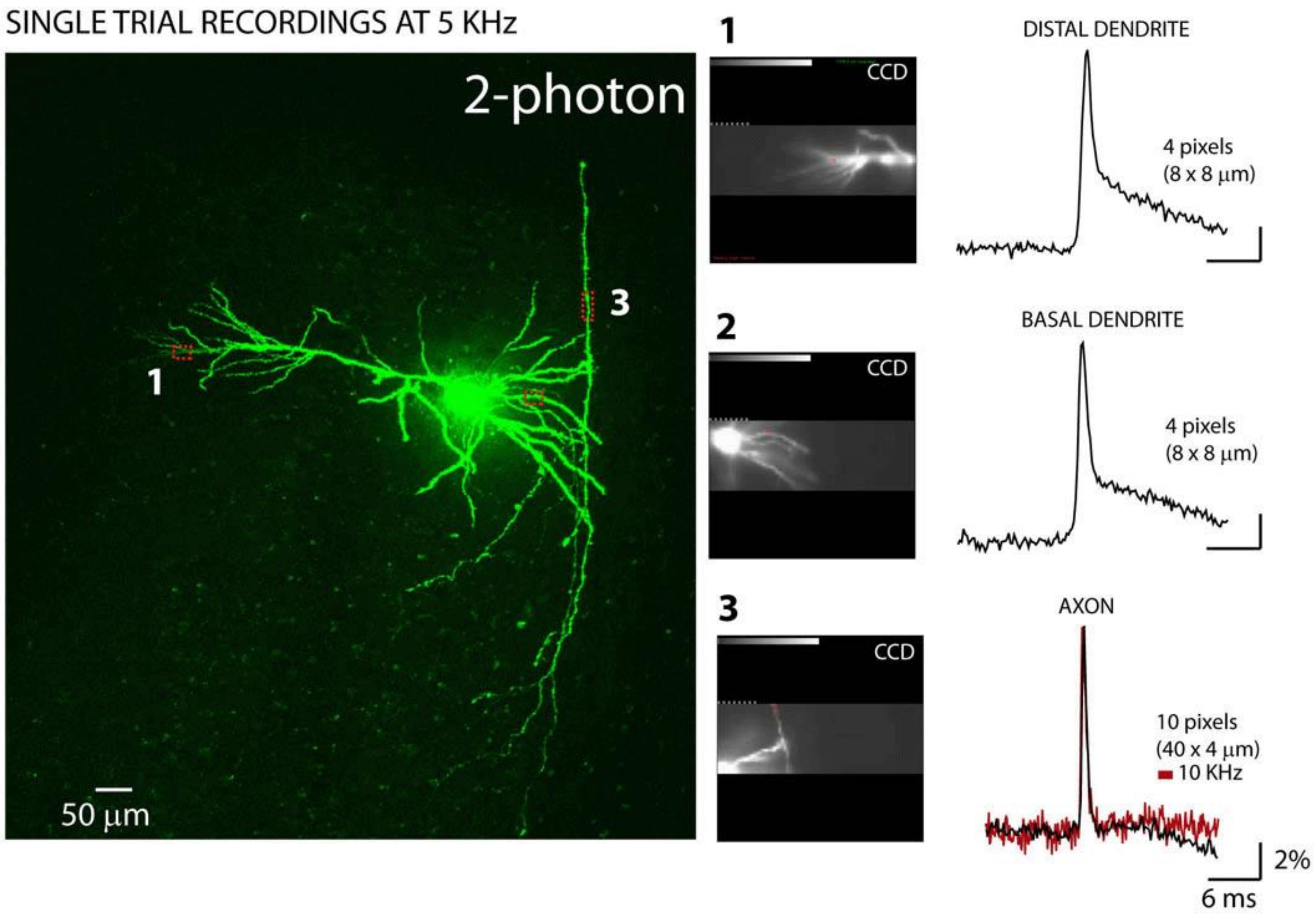
- One disadvantage of ECoG, is the relatively large size of ECoG electrodes
- These microelectrodes are only a fraction of a millimeter in diameter and spaced only 2–3 mm apart in a grid
- Allows detection of neural activity at a much finer resolution than traditional ECoG.
- Decoding fine movements, such as the movements of individual fingers, or even speech, without actually penetrating the brain.

Partially Invasive Approach

<u>Optical Recording: Voltage-Sensitive Dyes and Two-Photon Calcium Imaging:</u>

- Voltage-sensitive dyes
- Neurons are stained with a voltage-sensitive dye
- Dye responds to changes in membrane potential by changing its absorption and/or fluorescence
- Recorded optical signals correspond to summed responses from several simultaneously active neurons.
- Useful for imaging macroscopic features of the brain such as feature maps in the cortex

VOLTAGE-SENSITIVE DYE IMAGING



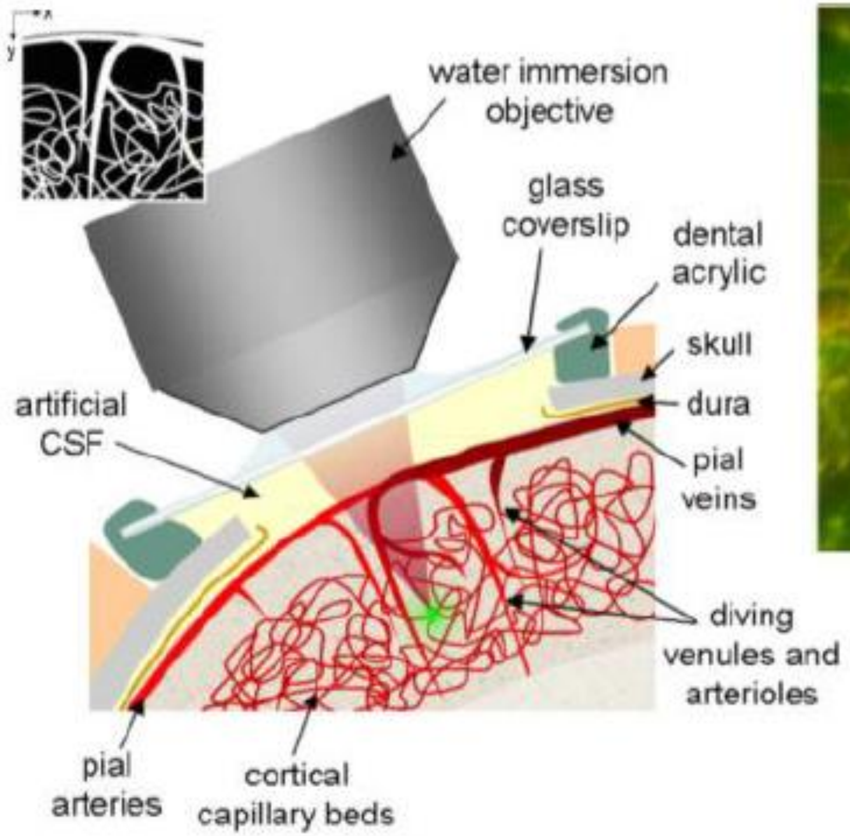
(image: Scholarpedia http://www.scholarpedia.org/article/Voltage-sensitive_dye).

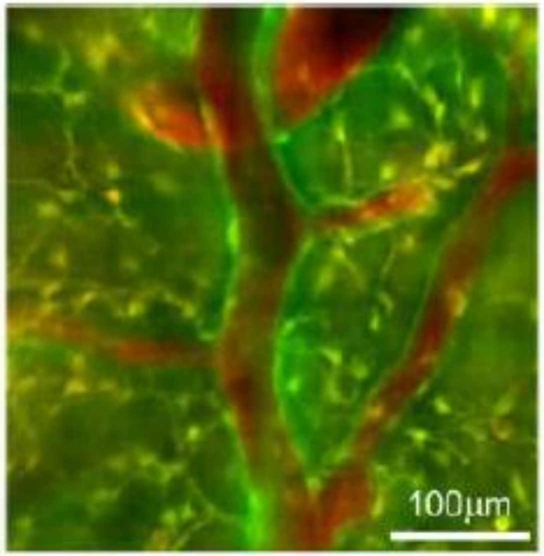
Partially Invasive Approach

- Two-photon calcium imaging
- Based on the fact that electrical activity in neurons is typically associated with changes in calcium concentration.
- Photon calcium imaging involves:

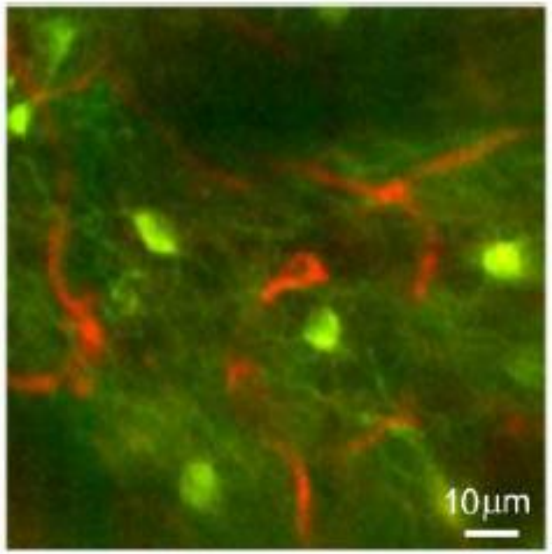
  (1) using pressure ejection to load neurons with fluorescent calcium-indicator dyes

  (2) monitoring changes in calcium fluorescence during neural activity using two-photon microscopy.





Oregon Green calcium sensitive dye stained neurons



Transgenic mouse expressing green fluorescent protein (GFP) in a subpopulation of neurons

Image from Kherlopian et al., 2008).

Non Invasive Approaches

Electroencephalography (EEG)

- EEG signals reflect the summation of postsynaptic potentials from many thousands of neurons that are oriented radially to the scalp.
- EEG predominantly captures electrical activity in the cerebral cortex, whose columnar arrangement of neurons and proximity to the skull favor recording by EEG.

Non Invasive Approaches

- Electroencephalography (EEG)
- The spatial resolution is typically poor (in the square centimeter range)
  - Due to lots of muscles between the source of signal and the electrodes placed on the scalp.

- The temporal resolution is good (in the milliseconds range)

Non Invasive Approaches

- The measured signals are in the range of a few tens of microvolts, necessitating the use of powerful amplifiers and signal processing to amplify the signal and filter out noise.
- Artifacts in the EEG signal
  - eye movements, eye blinks, eyebrow movements, talking, chewing, and head movements

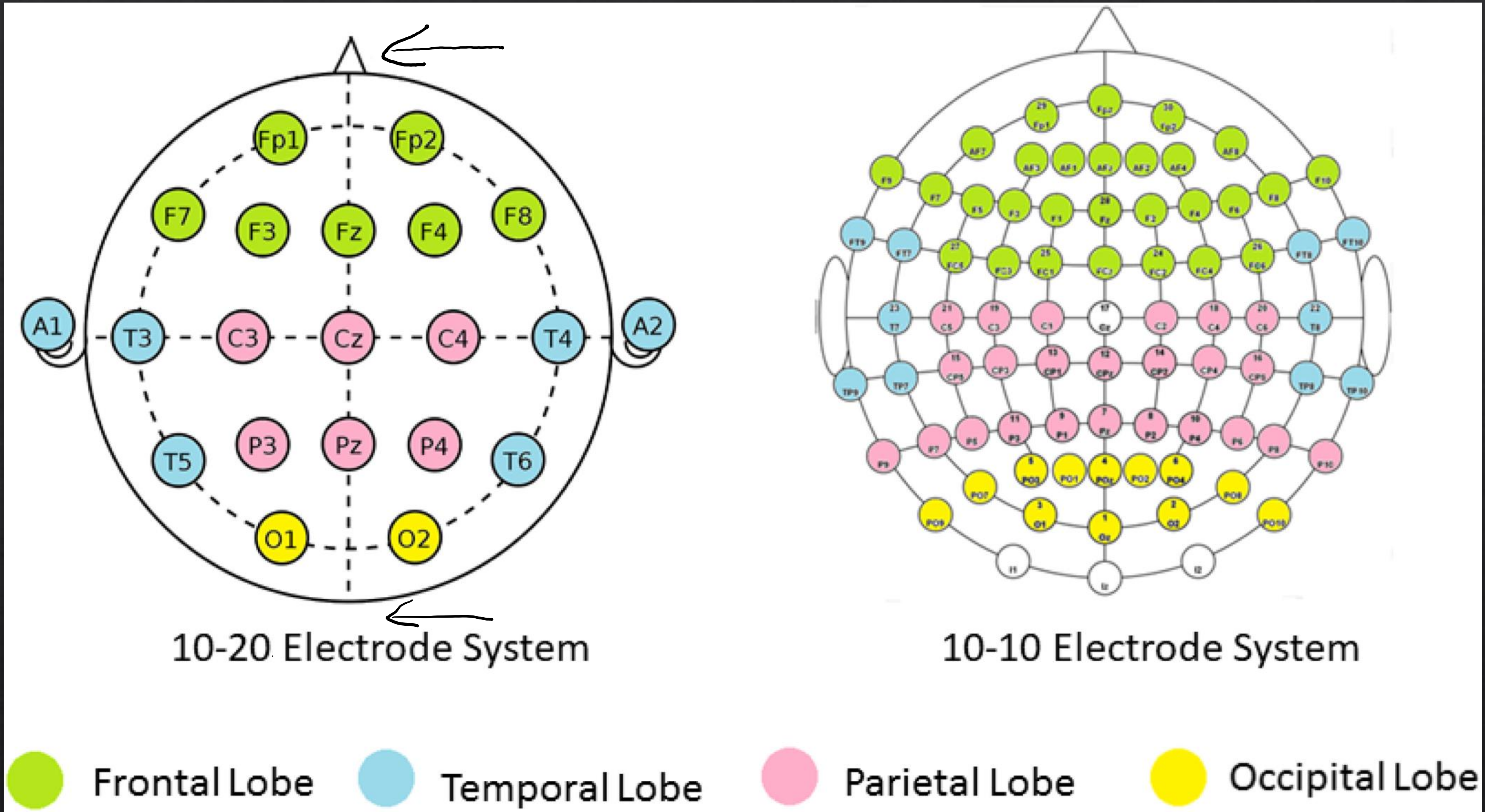
Non Invasive Approaches

- EEG recording involves the subject wearing a cap or a net into which the recording electrodes are placed
- A conductive gel or paste is injected into the holes of the cap before placing the electrodes.

courtesy K. Miller

Non Invasive Approaches

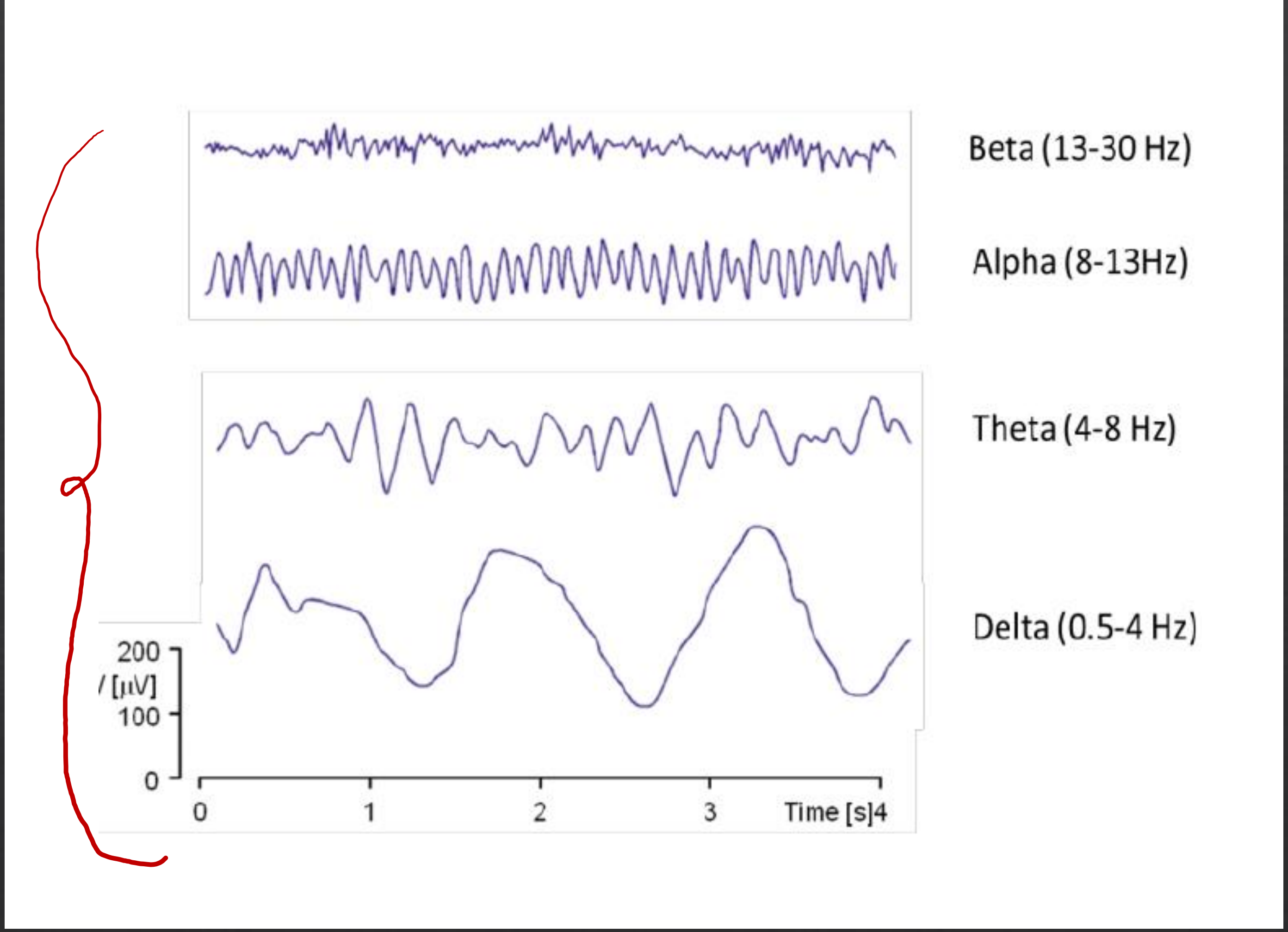
- The international 10–20 system is a convention used to specify standardized electrode locations on the scalp.
- C = central, P = parietal, T = temporal, F = frontal, Fp = frontal polar, O = occipital, A = mastoids


Fp1
Fp2
F7
F3
Fz
F4
F8
A1
T3
C3
Cz
C4
T4
A2
T5
P3
Pz
P4
T6
O1
O2
10-20 Electrode System
10-10 Electrode System
Frontal Lobe
Temporal Lobe
Parietal Lobe
Occipital Lobe

- The mastoids reference electrode locations behind each ear (A1 and A2).
- Other reference electrode locations are nasion, at the top of the nose, level with the eyes; and inion, at the base of the skull on the midline at the back of the head.
- In a typical setup, each EEG electrode is connected to one input of a differential amplifier, and the other input is connected to a reference electrode

- The amplification of voltage between the active electrode and the reference is typically 1,000–100,000 times.
- The amplified signal is passed through a filter and then digitized via an A/D (analog to digital) converter.
- After digitization, the EEG signal may be additionally filtered by a 1–50 Hz bandpass filter.
    - Excludes noise and movement artifacts in the very low and very high frequency ranges.

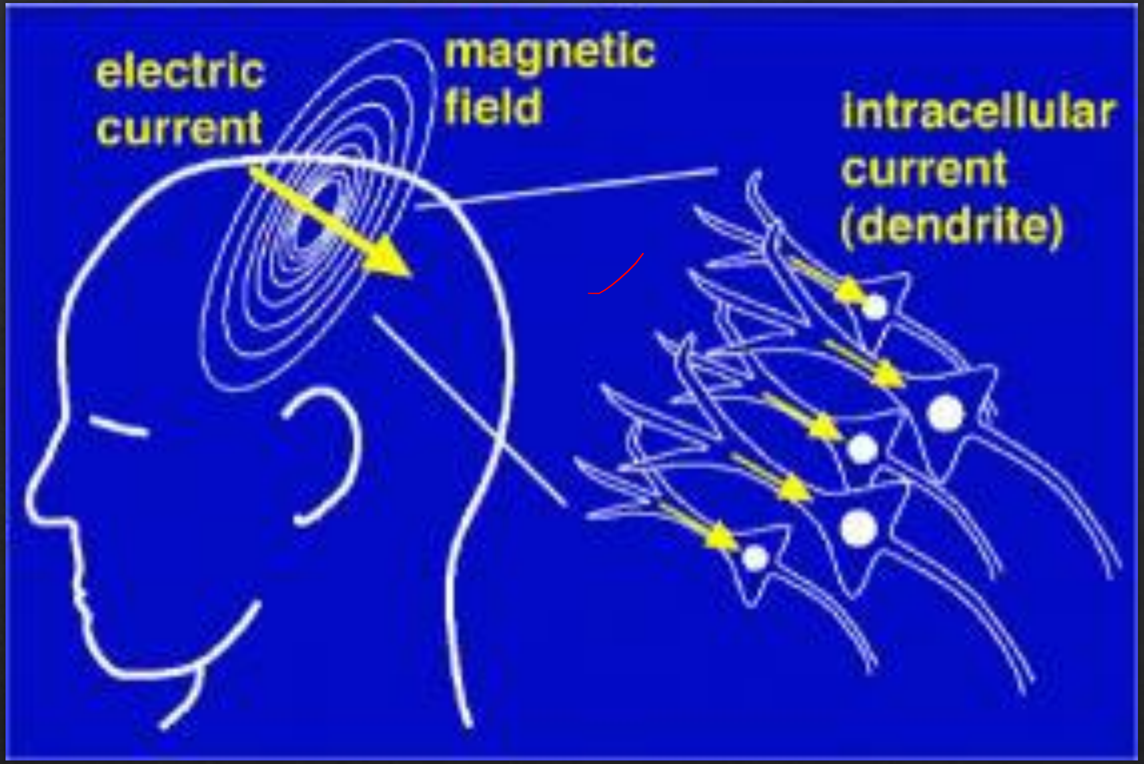
- EEG recordings are well-suited to capturing oscillatory brain activity or "brain waves" at a variety of frequencies
  - Alpha waves (8 to 13 Hz)
  - Beta waves (13 to 30 Hz)
  - Delta waves (0.5-4 Hz)
  - Theta waves (4-8 Hz)
  - Gamma waves (30-100 Hz or more)



Non Invasive Approaches

Magnetoencephalography (MEG):

- Measures magnetic fields produced by activity of thousands of cortical neurons oriented perpendicular to the cortical surface
- Magnetic fields not distorted by skull and scalp
- Better spatial resolution than EEG
- Expensive and bulky
- Magnetically shielded rooms

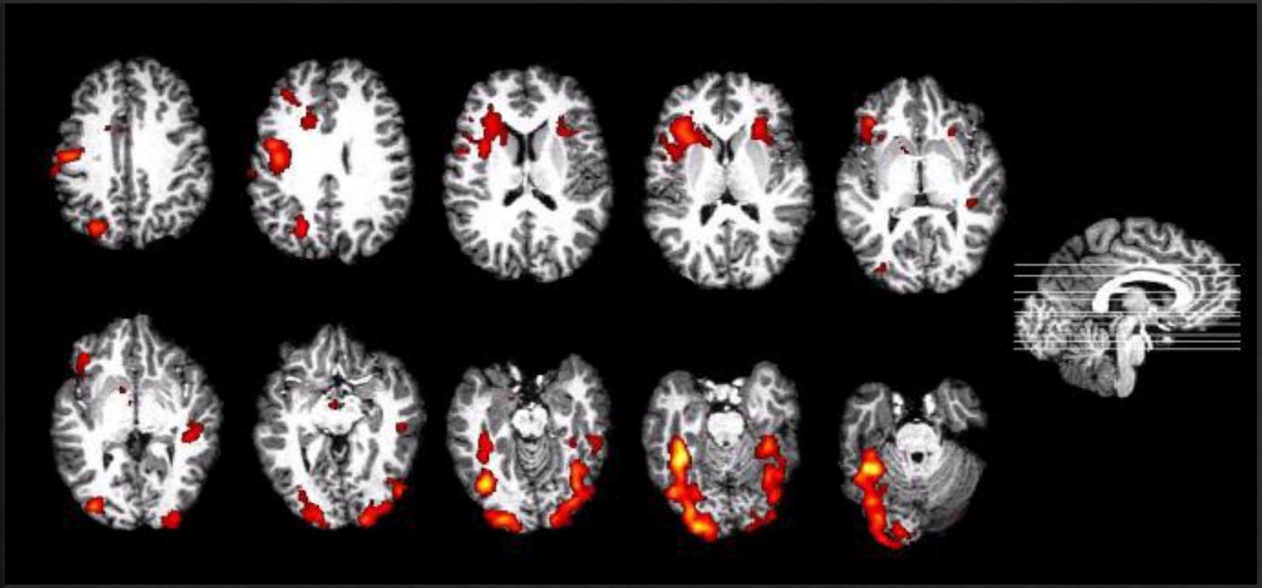


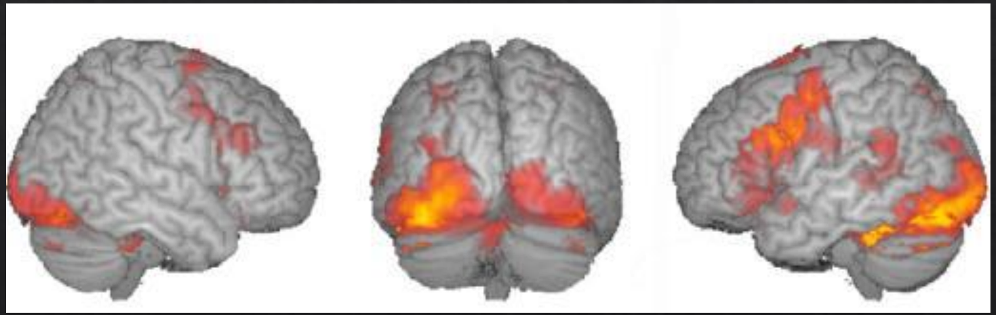
(image A: Wikimedia Commons;
image B: http://dateline.ucdavis.edu/photos_images/dateline_images/040309/DondersMEGOle_W2.jpg).

Non Invasive Approaches

Functional Magnetic Resonance Imaging (fMRI) :

- Measures changes in blood flow due to increased activation of neurons in an area
- Relies on paramagnetic properties of oxygenated and deoxygenated hemoglobin in the blood
- Produces images showing blood-oxygenation-level-dependent signal changes (BOLD)



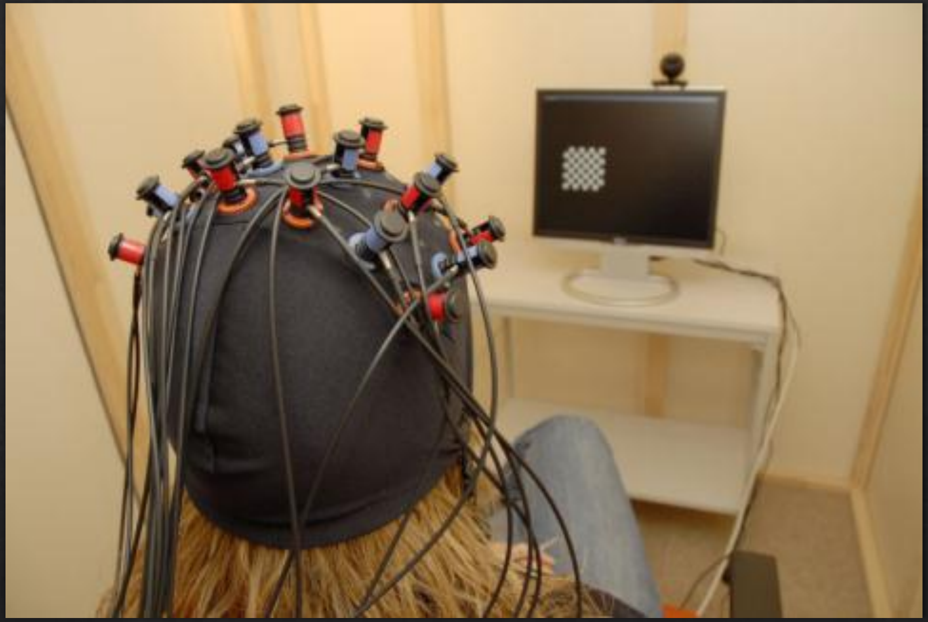


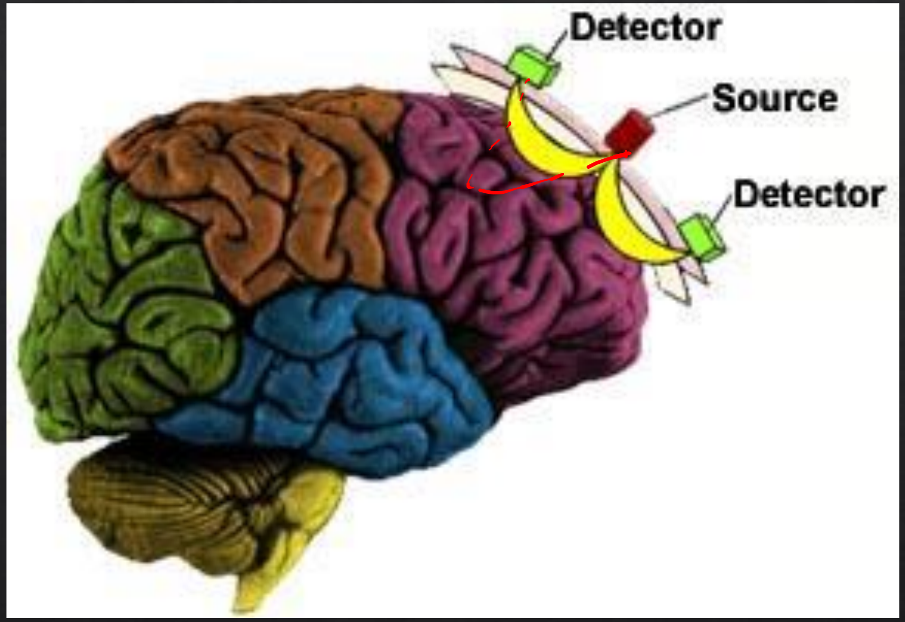
Example fMRI Images (word reading task)

Non Invasive Approaches

Functional Near-Infrared Spectroscopy (fNIR)

- Measures change in blood oxygenation level caused by increased neural activity in the brain.
- Based on detecting near-infrared light absorbance of hemoglobin in the blood with and without oxygen.
- Maps neural activity using "*optodes*" (emitters and detectors)

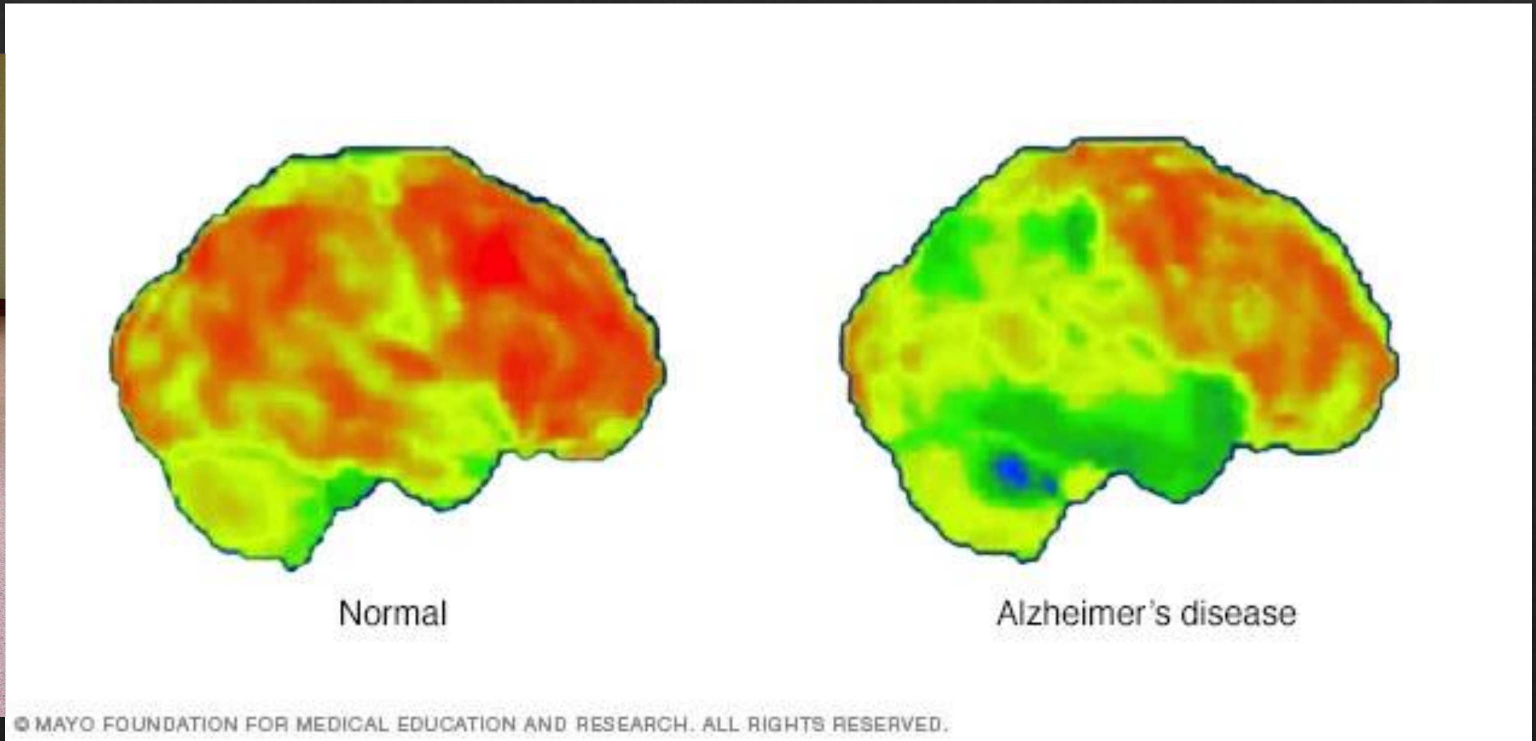



Detector
Source
Detector

Non-Invasive Approaches

- **Positron Emission Tomography (PET):**
- Measures emissions from radioactively labeled, metabolically active chemicals that have been injected into the bloodstream for transportation to the brain.
  - The labeled compound is called a *radiotracer*.

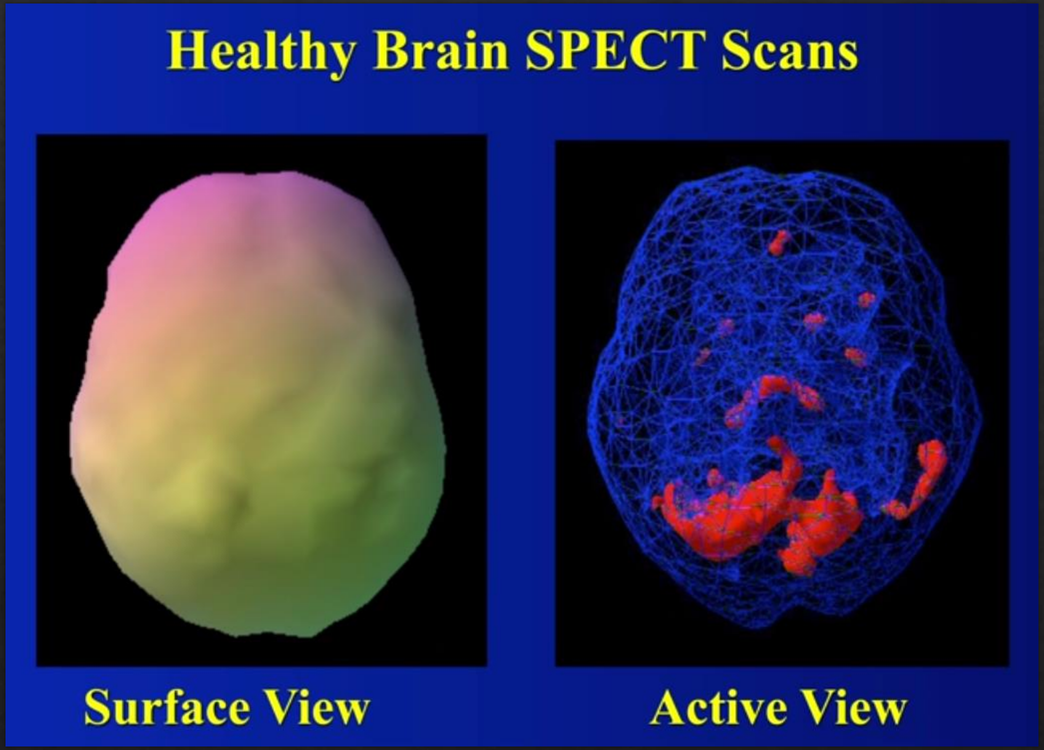
- Sensors in the PET scanner detect the radioactive compound
  - As a result of metabolic activity caused by brain activity.
- Generate two-or three-dimensional images indicating the amount of brain activity.



A PET scan can compare a normal brain (left) with one affected by Alzheimer's disease (right). An increase in blue and green colors shows decreased brain metabolic activity due to Alzheimer's disease.

Non Invasive Approaches

- Single-photon emission-computed tomography (**SPECT**):
- SPECT is a nuclear medicine technique that uses gamma rays to study the brain.
- A radioactive substance is injected into the patient's body and is scanned using a SPECT machine.
- Allows doctors to see how blood flows into tissues and organs.
  - Active, inactive, or overactive.
- Averages the brain activity over a few minutes and generates an image.



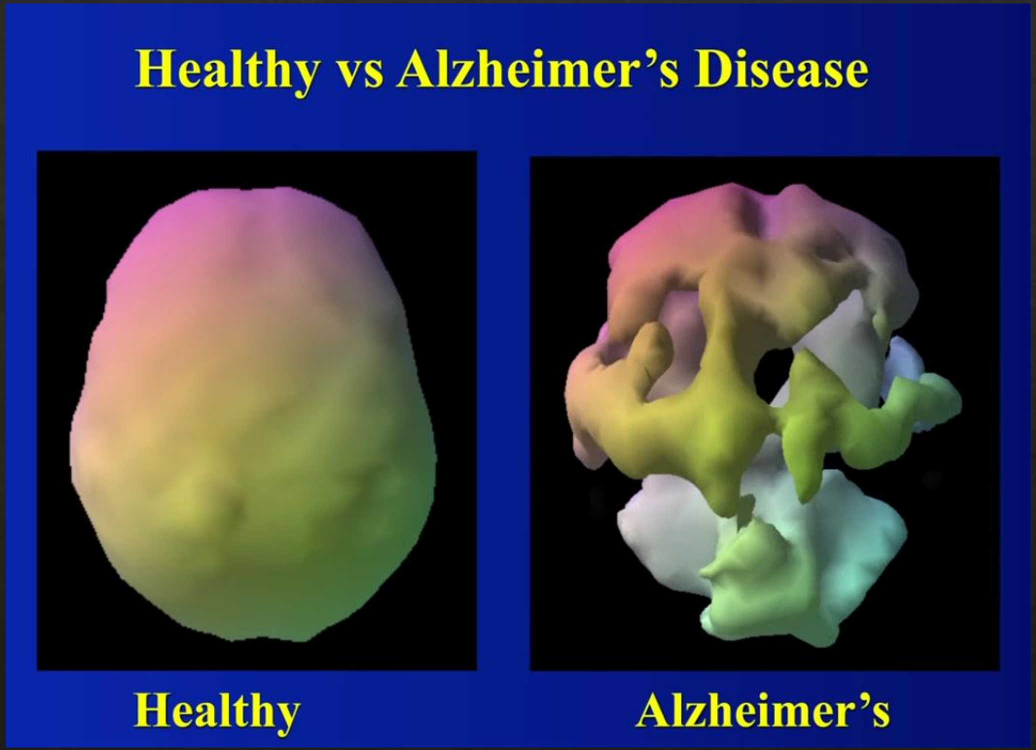


Image credit: https://hamnaqasim.medium.com/brain-scans-a-lesson-to-learn-9dfe67abd841

EEG Measure

Course Instructor

Dr. Annushree Bablani

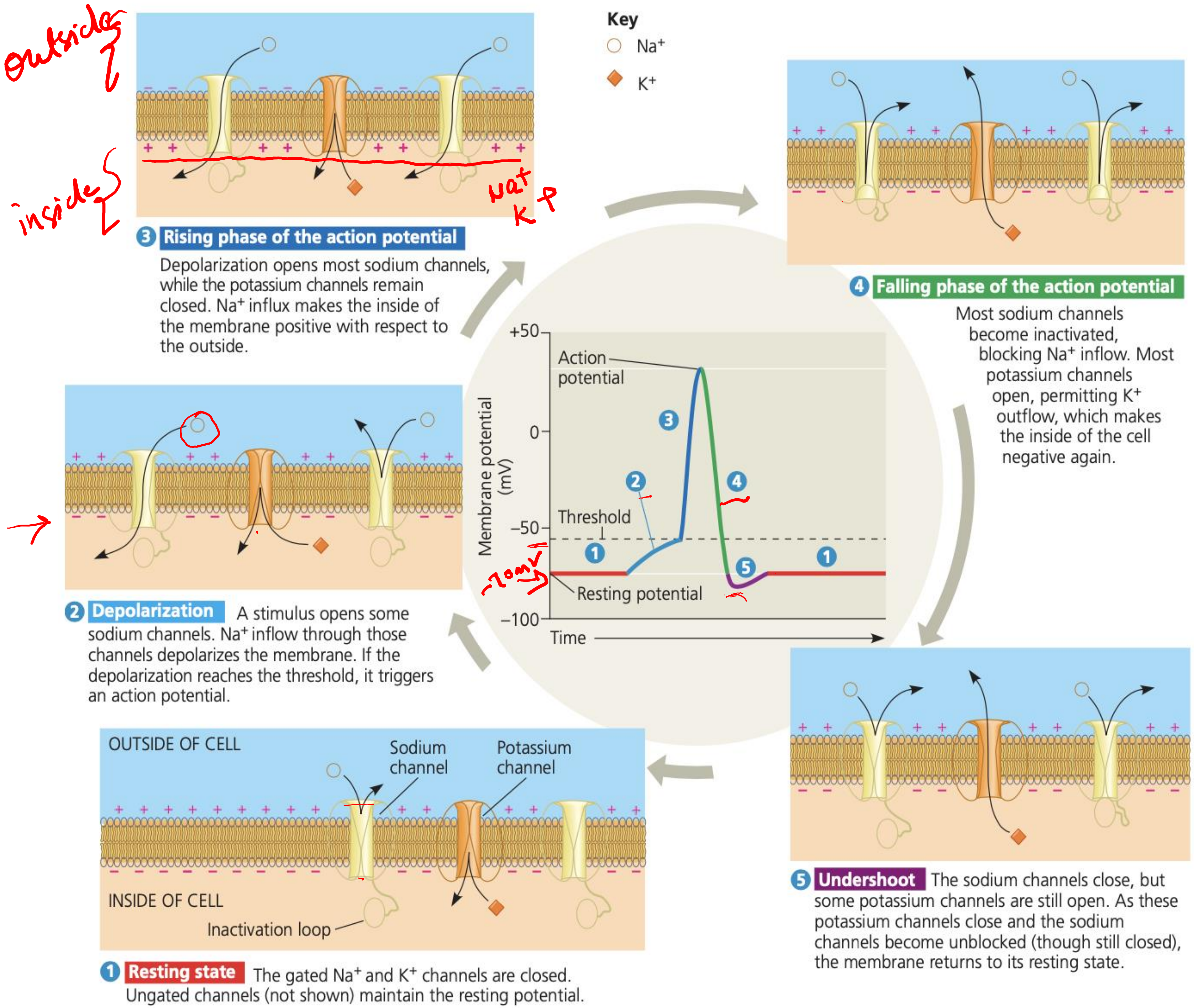
Acknowledgments: Dr Sreeja SR

REVISIT

- **Neurons** are nerve cells that transfer information within the body
- Neurons use two types of signals to communicate: electrical signals (long-distance) and chemical signals (short-distance)
- Nervous systems process information in three stages: sensory input, integration, and motor output

Hyperpolarization and Depolarization

- Changes in membrane potential occur because neurons contain **gated ion channels** that open or close in response to stimuli.
- When gated K^+ channels open, K^+ diffuses out, making the inside of the cell more negative. This is **hyperpolarization**, a reduction in magnitude of the membrane potential.
- Opening other types of ion channels triggers a **depolarization**, an increase in the magnitude of the membrane potential. For example, depolarization occurs if gated Na^+ channels open and Na^+ diffuses into the cell.
- **Graded potentials** are changes in polarization where the magnitude of the change varies with the strength of the stimulus.
- If a depolarization shifts the membrane potential sufficiently, it results in a massive change in membrane voltage called an **action potential.**


Key
Na+
K+
outside
inside
Na+
K+
3 Rising phase of the action potential
Depolarization opens most sodium channels, while the potassium channels remain closed. Na+ influx makes the inside of the membrane positive with respect to the outside.
4 Falling phase of the action potential
Most sodium channels become inactivated, blocking Na+ inflow. Most potassium channels open, permitting K+ outflow, which makes the inside of the cell negative again.
+50
0
−50
−70mV
−100
Membrane potential (mV)
Action potential
Threshold
Resting potential
Time
2 Depolarization A stimulus opens some sodium channels. Na+ inflow through those channels depolarizes the membrane. If the depolarization reaches the threshold, it triggers an action potential.
OUTSIDE OF CELL
Sodium channel
Potassium channel
INSIDE OF CELL
Inactivation loop
1 Resting state The gated Na+ and K+ channels are closed. Ungated channels (not shown) maintain the resting potential.
5 Undershoot The sodium channels close, but some potassium channels are still open. As these potassium channels close and the sodium channels become unblocked (though still closed), the membrane returns to its resting state.

Generation of Postsynaptic Potentials

- Direct synaptic transmission involves binding of neurotransmitters to **ligand-gated ion channels** in the postsynaptic cell.
- Neurotransmitter binding causes ion channels to open, generating a postsynaptic potential.
- Postsynaptic potentials fall into two categories
  - **Excitatory postsynaptic potentials (EPSPs)** are depolarizations that bring the membrane potential toward threshold.
  - **Inhibitory postsynaptic potentials (IPSPs)** are hyperpolarizations that move the membrane potential farther from threshold.

What are we measuring with EEG?

What does the EEG record?

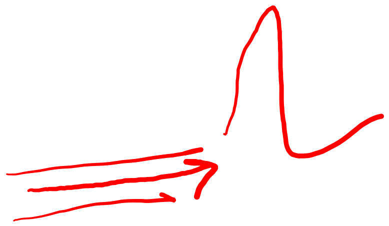
Mainly NOISE!!

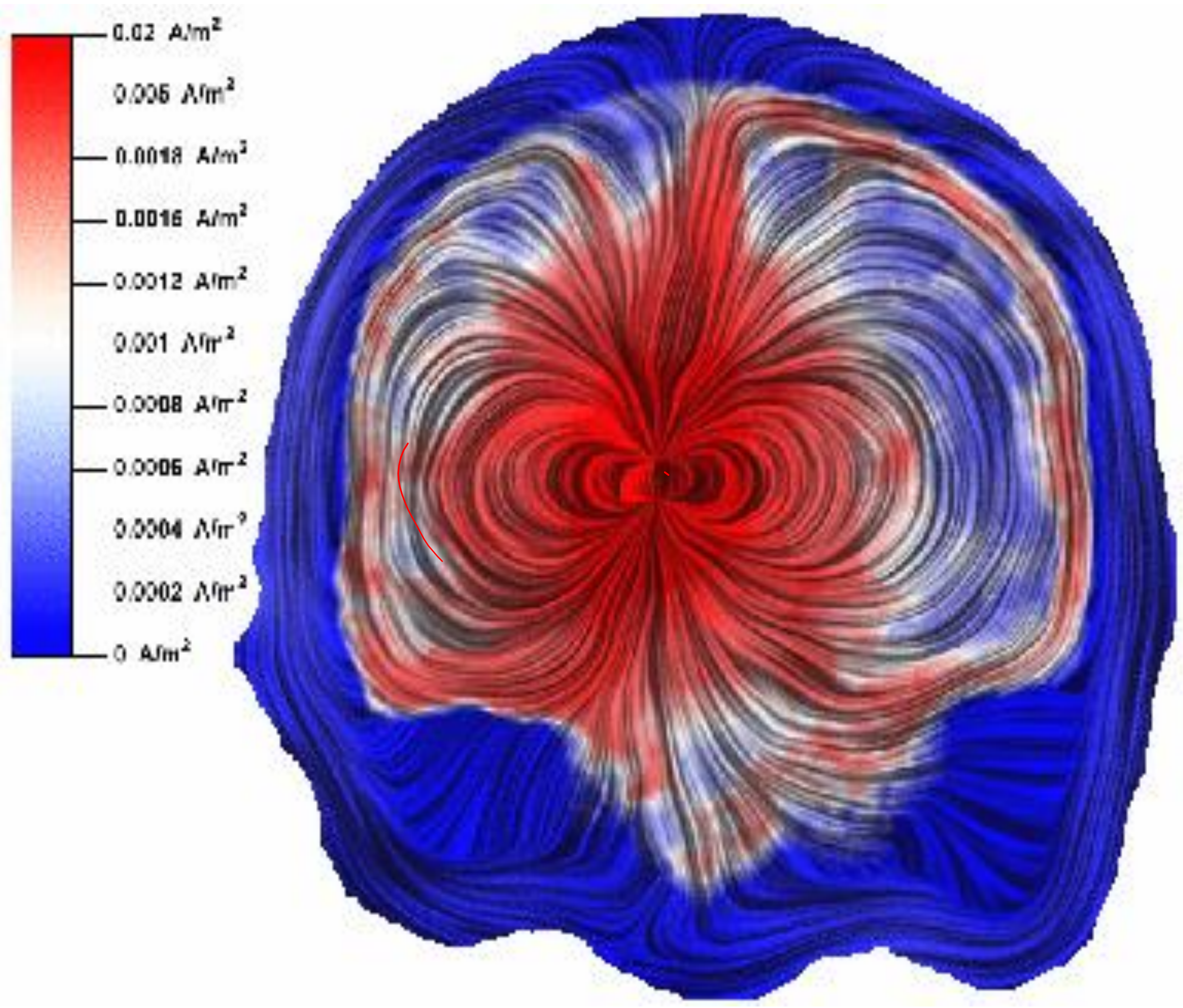
Volume Conduction

EEG directly measures the neural activity.

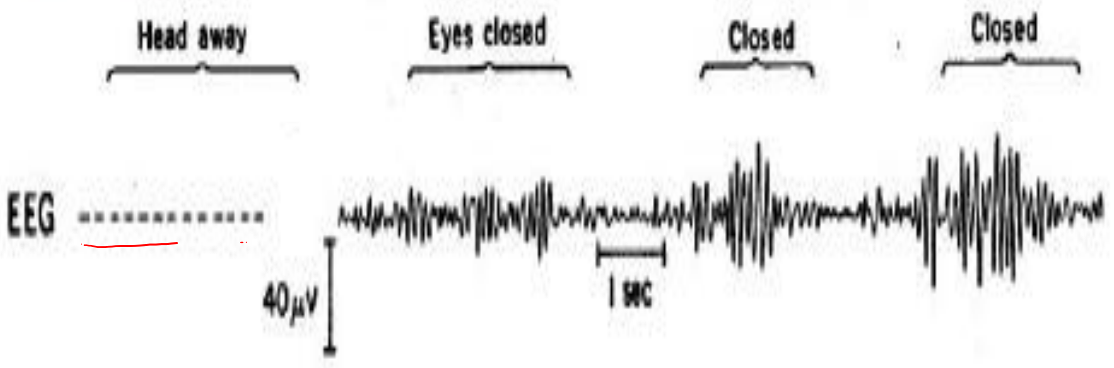
What kind of neuronal activity?

- Action potentials
- Postsynaptic potentials



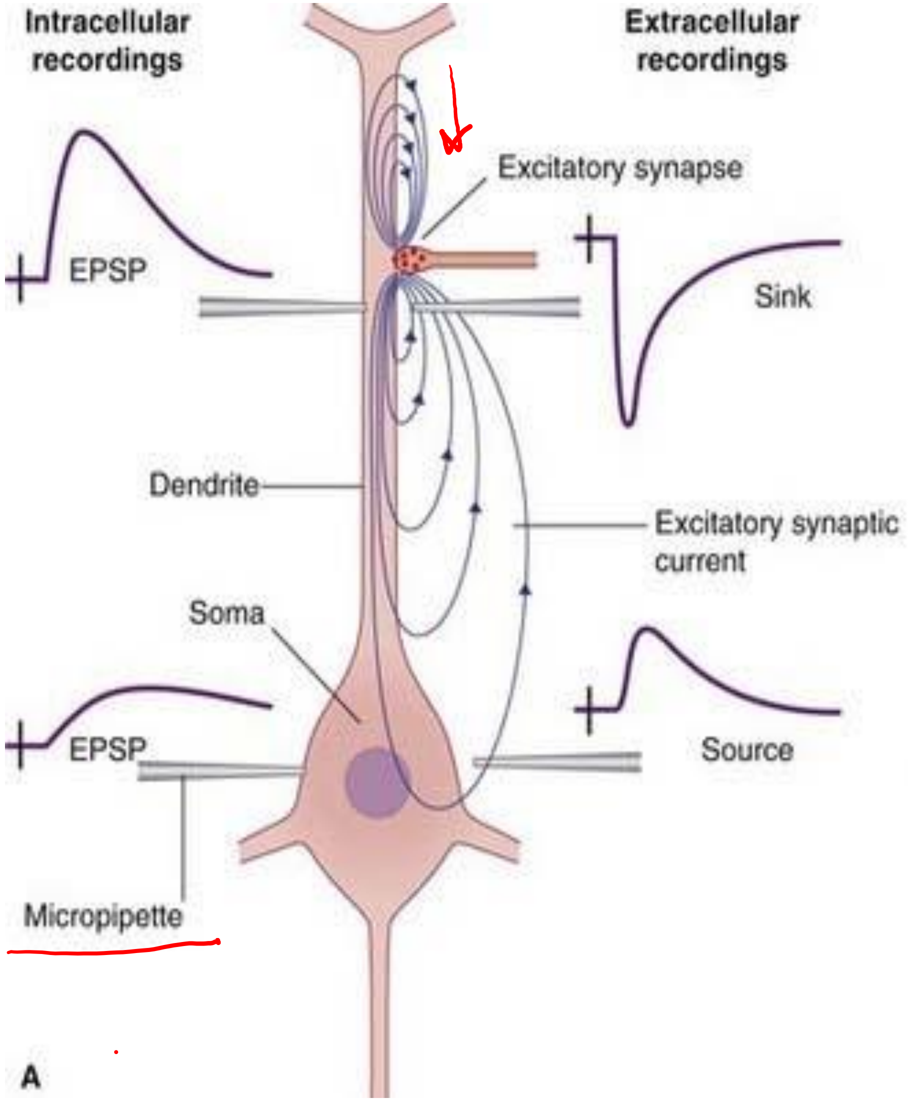


EEG measures the underlying neural currents



- **EEG**: Measures differences in electric potential at the scalp.
- Non-invasive, cover the whole head, and have very high temporal resolution.

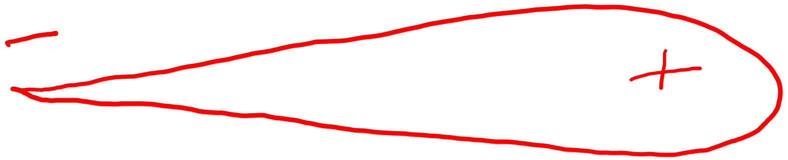
Neural basis of the EEG



When an EPSP is generated in the dendrites of a neuron an extracellular electrode detects a negative voltage difference, resulting from Na^+ currents flowing inside the neuron’s cytoplasm.

The current completes a loop further away the excitatory input (Na^+ flows outside the cell), being recorded as a positive voltage difference by an extracellular electrode.

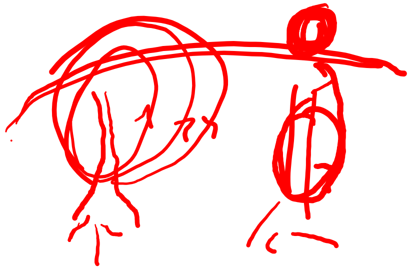
This process can last hundreds of milliseconds.

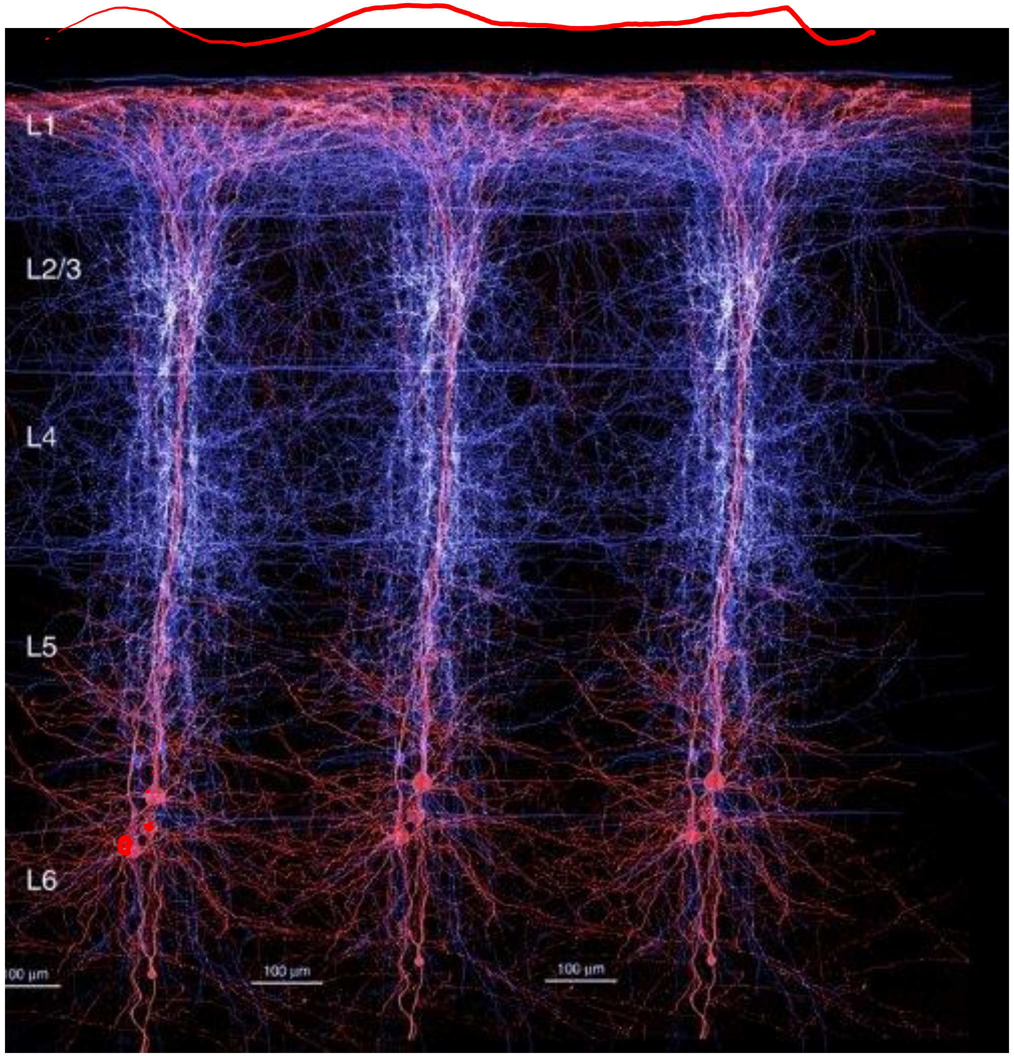


https://clinicalgate.com/electroencephalography/

From single neuron to neural population

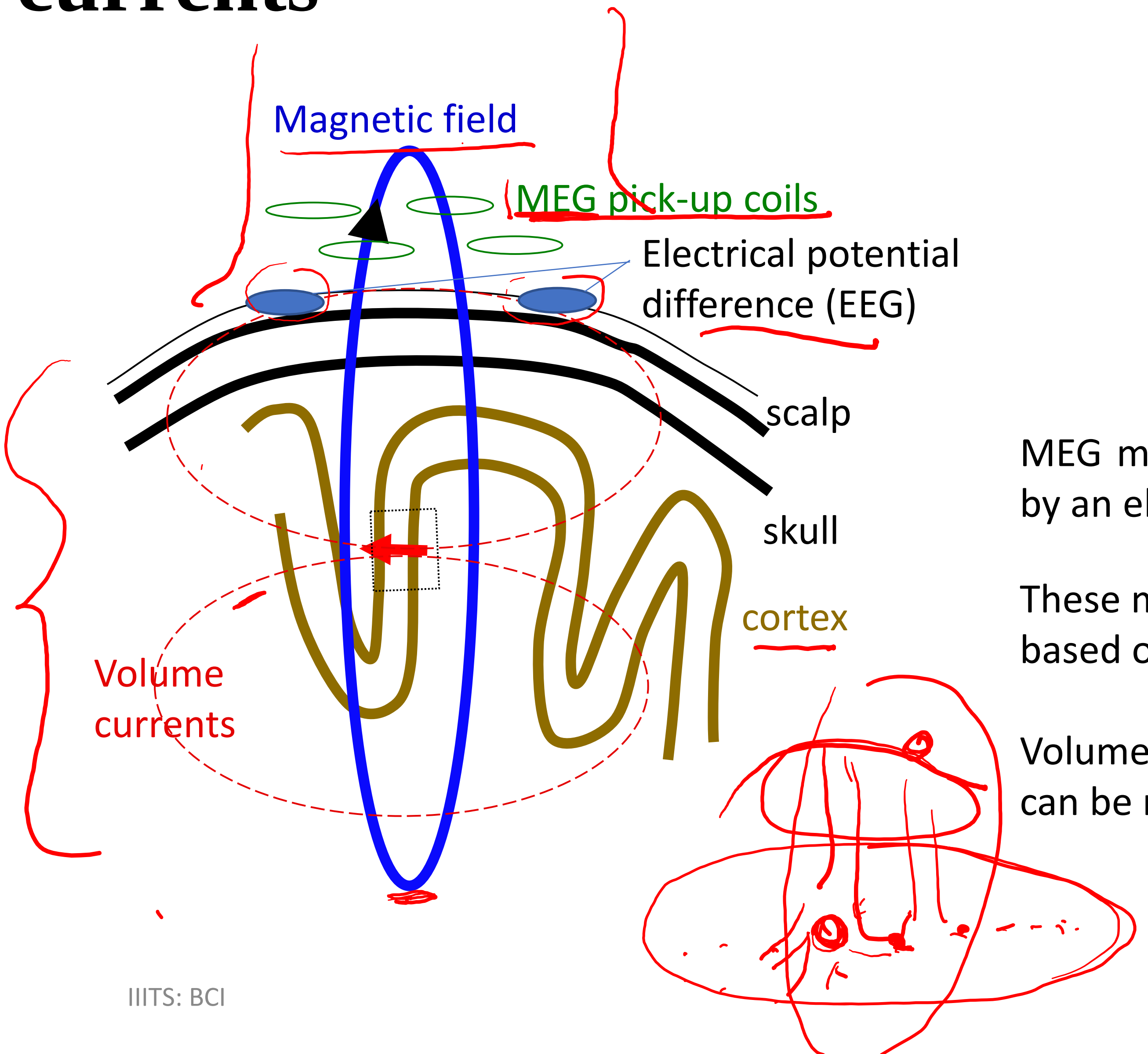
- The geometry of the neuron must give rise to a net dipole current to contribute to the EEG signal.
- A large number of neurons have to be active simultaneously to generate a measurable EEG signal.
- Pyramidal neurons are spatially aligned and perpendicular to the cortical surface.
- Thus, EEG represents mainly the postsynaptic potentials of pyramidal neurons close to the recording electrode.
- The electrical activity from deeper generators gets dispersed and attenuated by volume conduction effects.

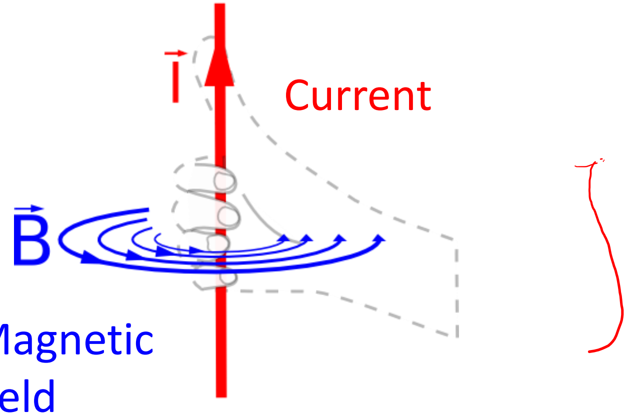




BBP/EPFL

Primary intracellular currents give rise to volume currents





MEG measures the changes in the magnetic field generated by an electric current (Sarvas 1987, Hämäläinen 1993)

These magnetic fields are mainly induced by primary currents based on excitatory activity (Okada et al. 1997)

Volume currents yield potential differences on the scalp that can be measured by EEG.

- The connection between electricity and magnetism was first discovered by Hans Christian Orsted in 1819.
- He demonstrated that a magnetic compass needle was affected by a current passing through a circuit.
- An electrical dipole is always surrounded by a corresponding magnetic field.
- The polarity of the field is determined by the direction of the current.

History

1929: Hans Berger developed the electroencephalography (=graphic representation of the difference in voltage between two different cerebral locations plotted over time) following the studies of Richard Caton in non-human animal species.

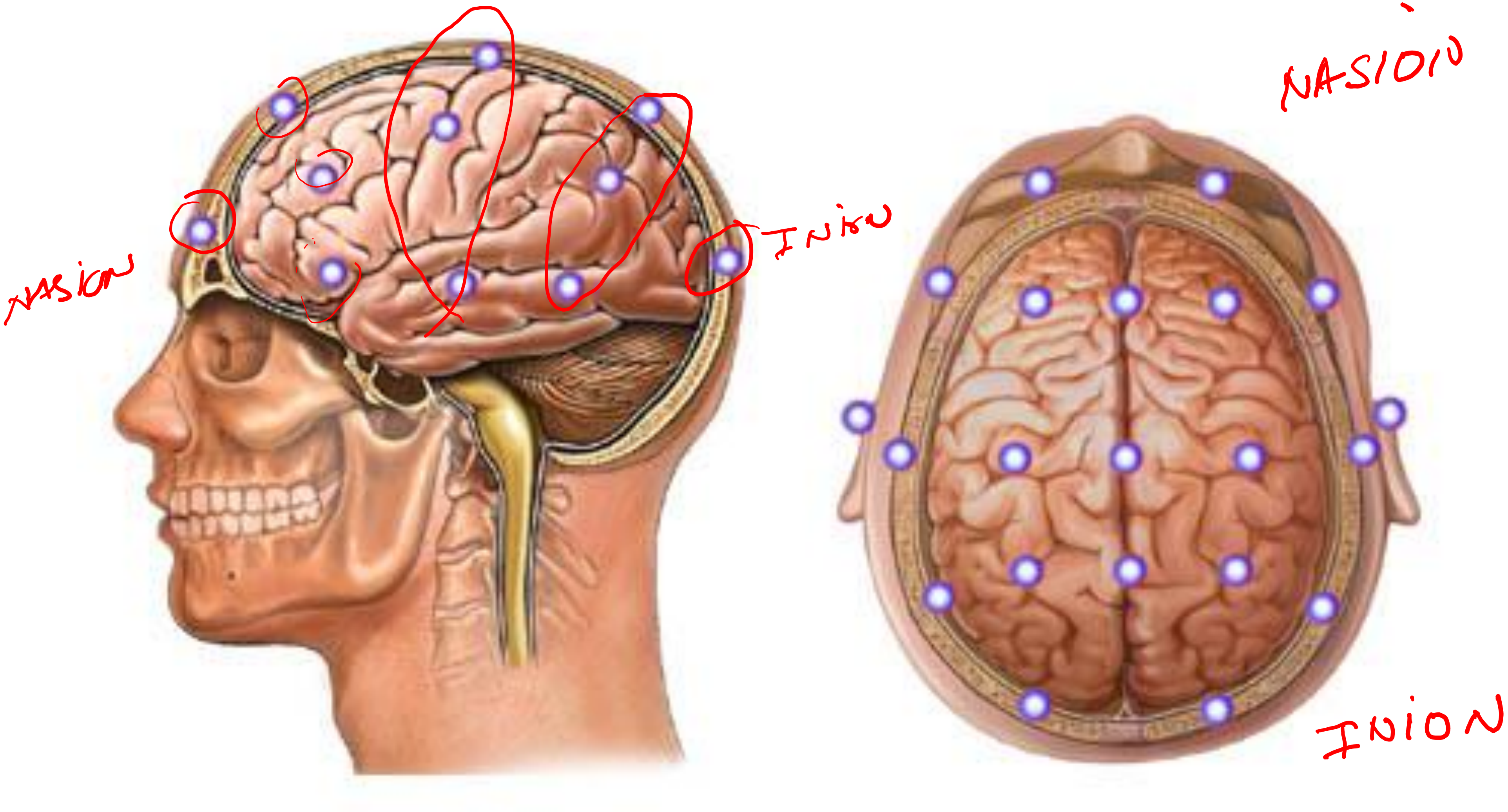
He described the human alpha and beta rhythms.

8-13 HZ

Berger waves

High density EEG recording

Electrode placing locations in EEG



Electr... ation in EEG

The names of the electrode sites use alphabetical abbreviations that identify the lobe or area of the brain to which each electrode refers:

F = frontal

Fp = frontopolar

T = temporal

C = central

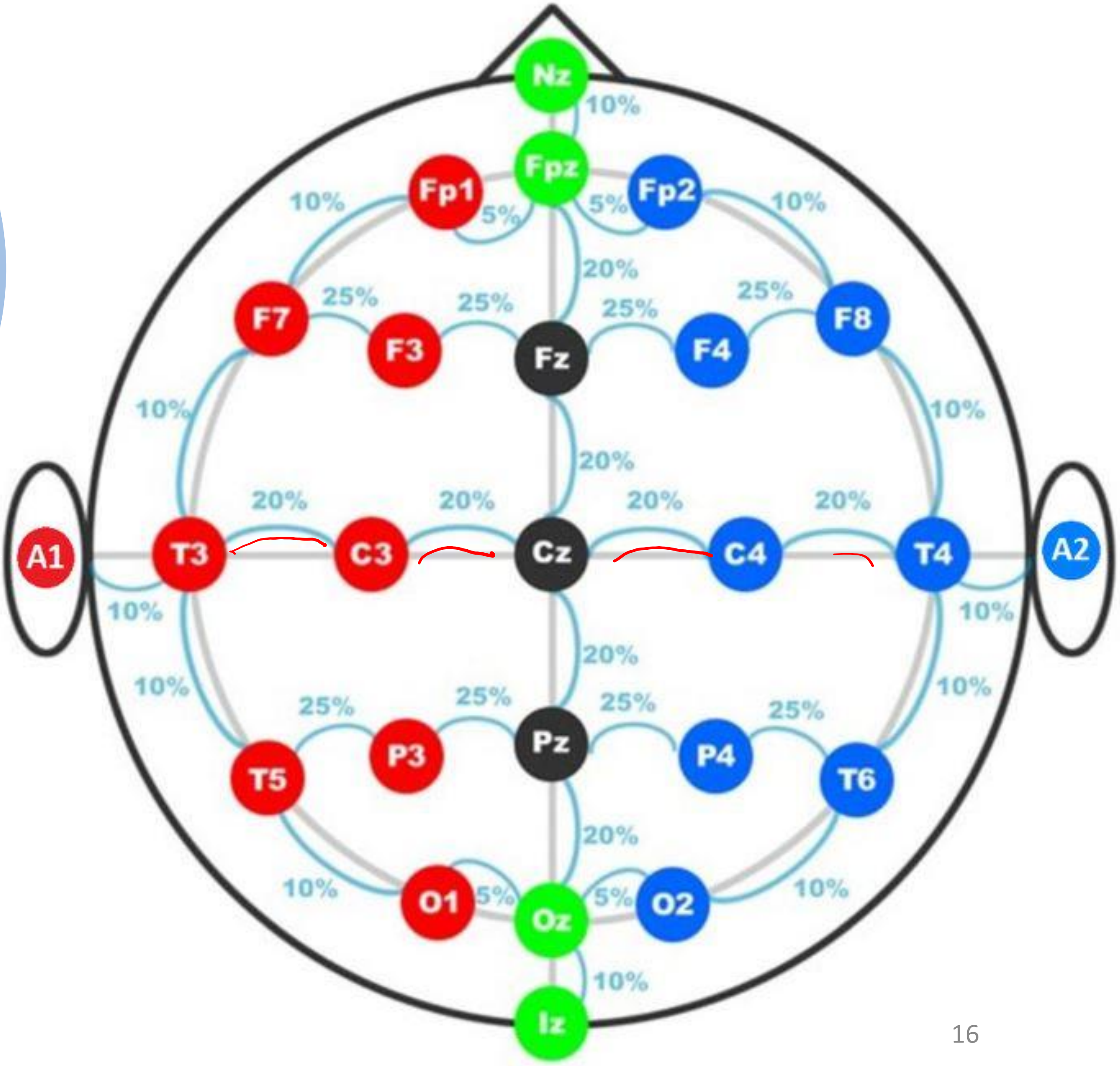
P = parietal

O = occipital

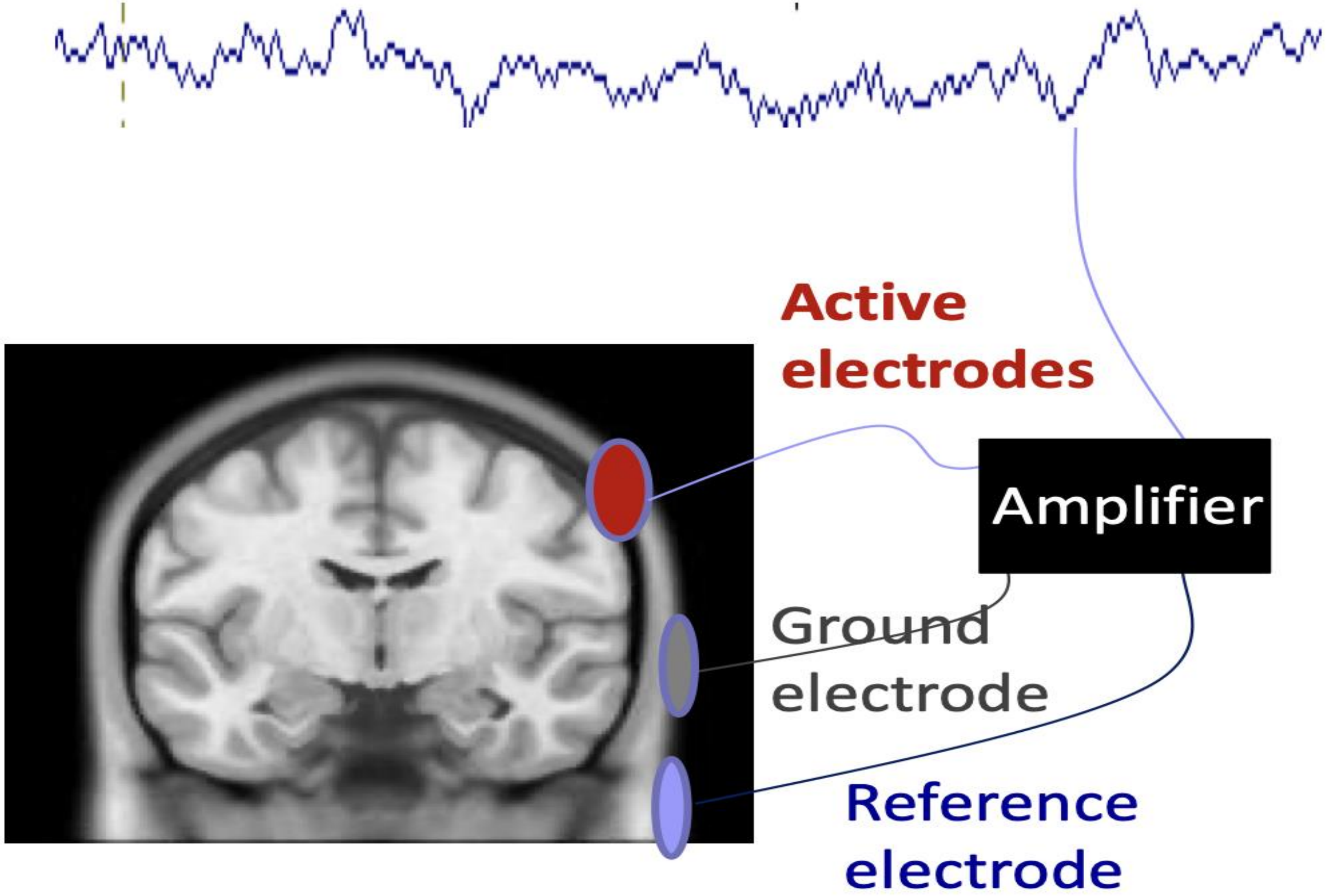
A = auricular (ear electrode)

"z" refers to an electrode placed on the mid-line

❖ **Even numbers** denote the right side of the head and **odd numbers** the left side of the head.



Measuring EEG…



Measuring EEG…

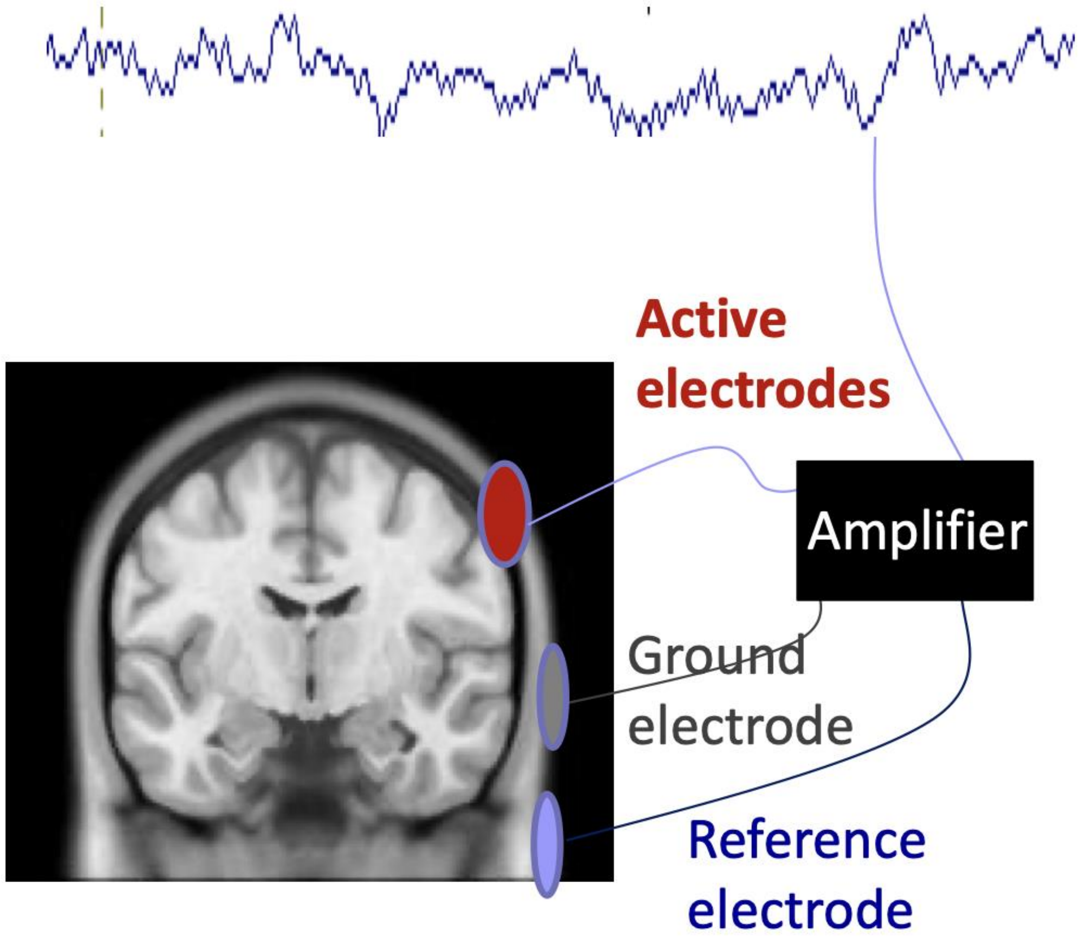
Electric fields affecting measurements:

1. Static electric current
2. Electric noise
3. Brain activity

Ground = difference between the participant and the amplifier

➔Subtracted from the active and reference electrode activity: A-G, R-G

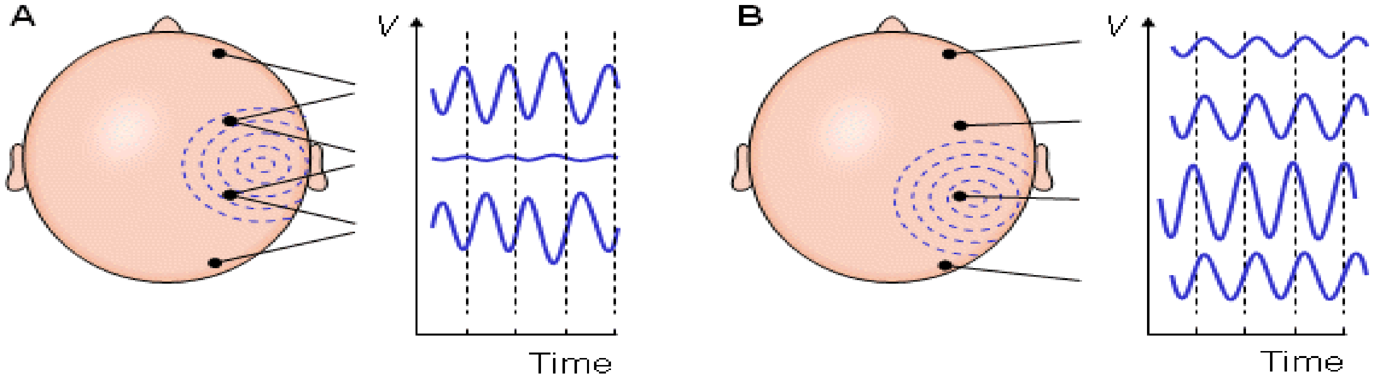
➔is the reference point in an electrical circuit from which voltages are measured, a common return path for electric current, or a direct physical connection to the Earth.



An EEG Device

Measuring EEG…

- EEG records potential differences at the scalp using a set of electrodes and a reference.
- The ground electrode is important to eliminate noise from the amplifier circuit.
- The representation of the EEG channels is referred to as a montage
  - Unipolar/Referential ⇒ potential difference between electrode and designated reference
  - Bipolar ⇒ represents difference between adjacent electrodes (e.g. ECG, EOG)
- Potential differences are then amplified and filtered



Thank you!!

EEG Paradigms

<u>Course Instructor</u>

Dr. Annushree Bablani

Acknowledgments: Dr Sreeja SR

Direct (noninvasive) interfaces in EEG

- An event-related potential (ERP) is any measured brain response that is directly the result of a thought or perception. More formally, it is any stereotyped electrophysiological response to an internal or external stimulus.

- Direct Interfaces via EEG
  - VEP – Visual Evoked Potential
  - AEP – Auditory Evoked Potential
  - SSVEP – Steady-State Visual Evoked Potential
  - P300 – ERP elicited by infrequent, task-relevant stimuli.
  - ERS/ERD – Event related synchronization/desynchronization
  - SCP – Slow cortical potentials

Categorization of EEG based BCI paradigms

Evoked (Endogenous / Asynchronous)

- Subject must pay attention for a certain time to external cues (e.g. flashes, sounds, etc.)
- Cue-based

Spontaneous (Exogenous / Synchronous)

- No continuous attention to specific stimulus is necessary
- User-driven

Categorization of EEG based BCI paradigms

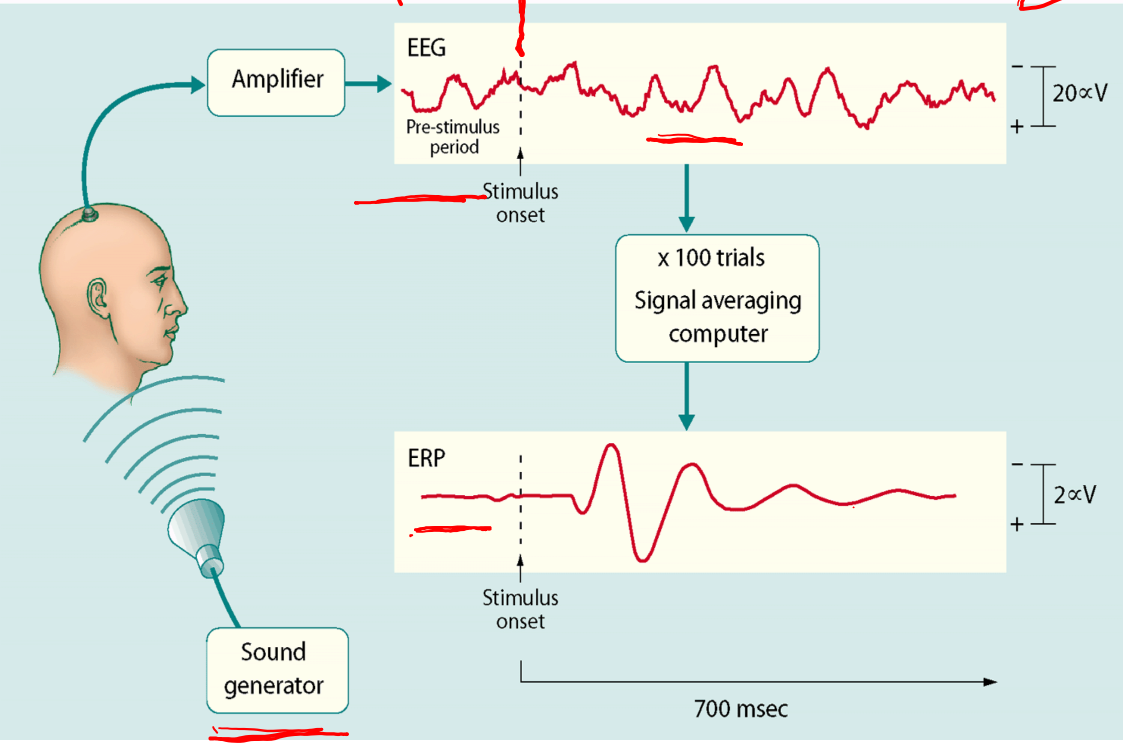
ERD	Spontaneous
P300	Evoked
SSEP/AEP/VEP	Evoked
SCP	Spontaneous

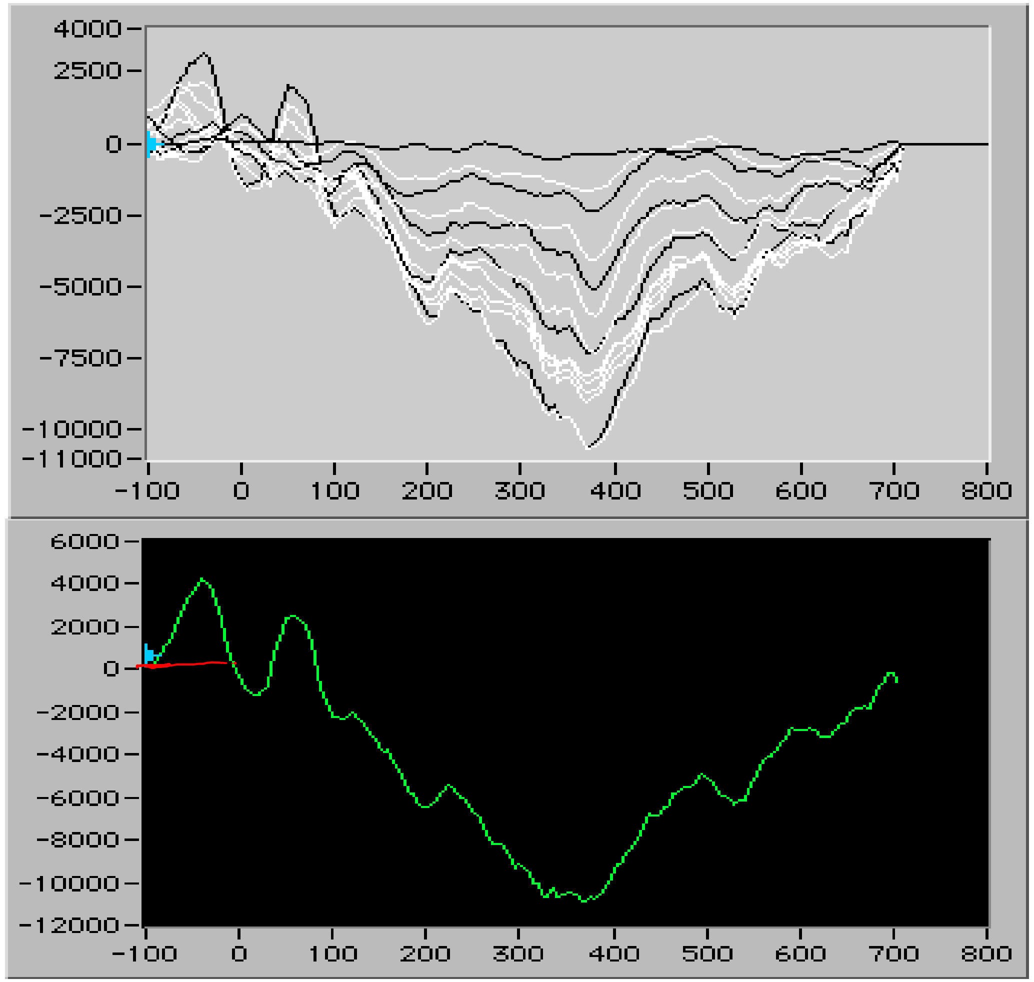
Event Related Potentials (ERP)

→ deflections → +ve P100
→ -ve N100

- Averaging of trials following a stimulus

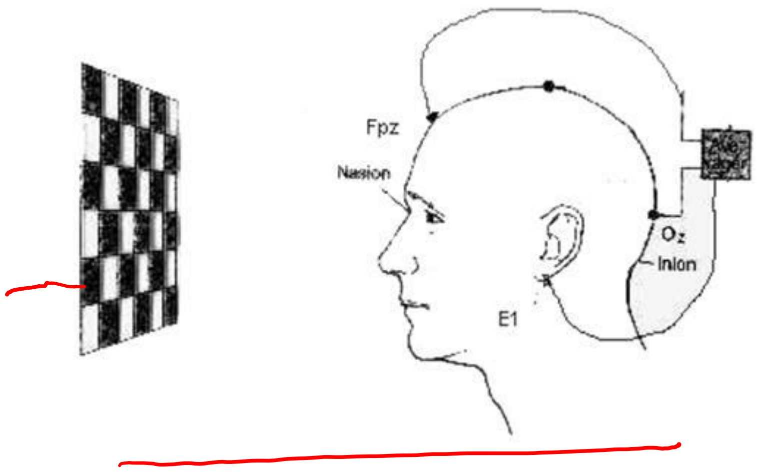
Marker

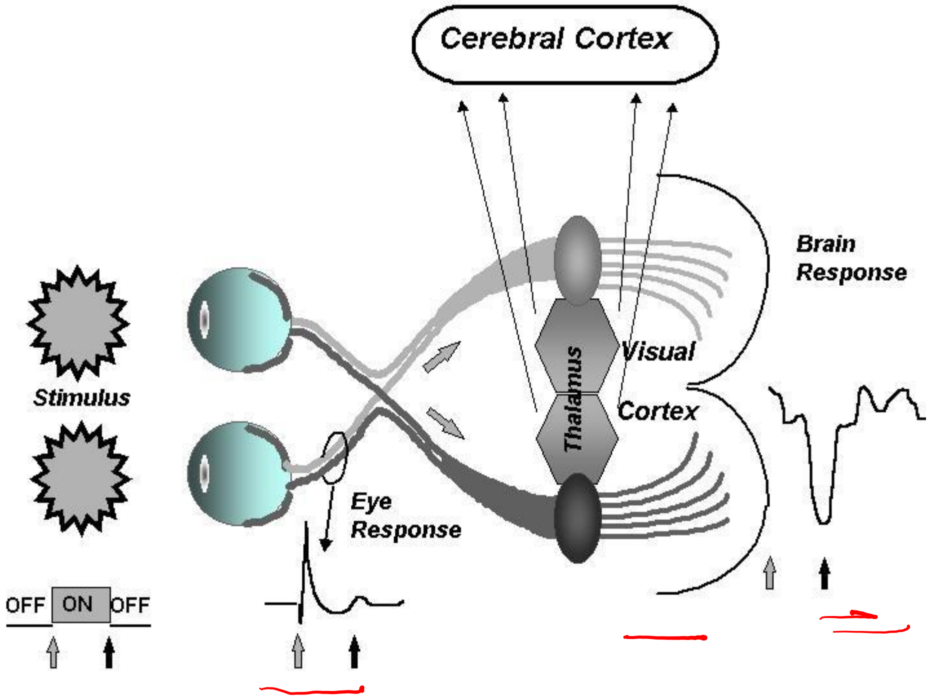




Visual Evoked Potential (VEP)

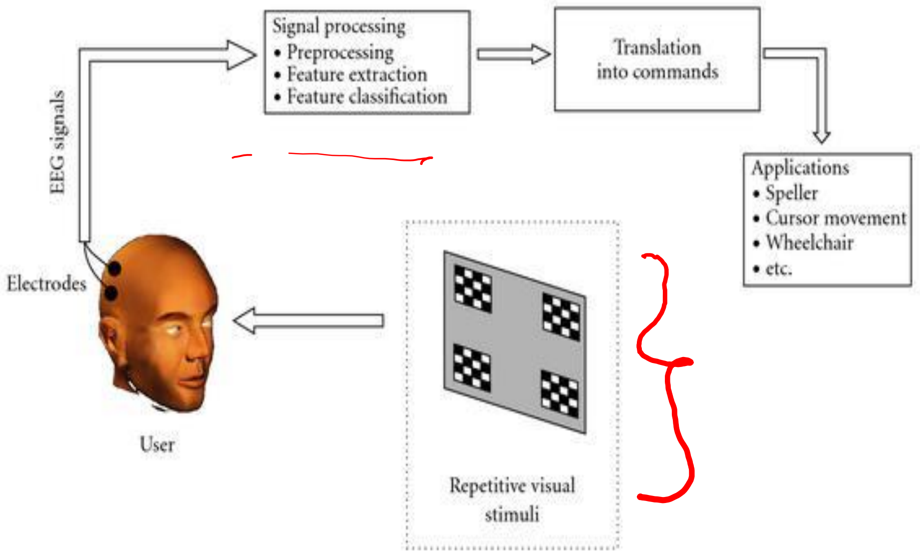
- **Caused by Visual Stimulus**
- **Occurs with flashing lights (3-5 Hz)**
- **Have been used to monitor function during surgery for lesions involving the pituitary gland, optic nerve.**
- **Application:**





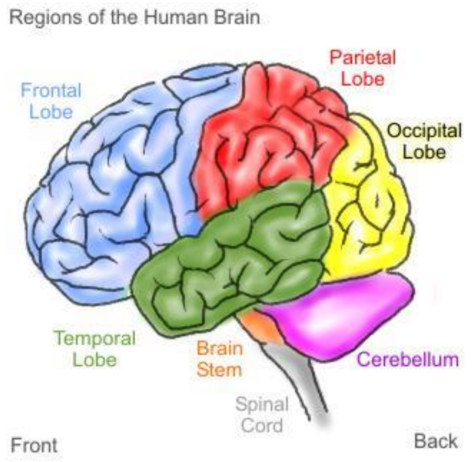
Steady-State Visual Evoked Potential (SSVEP)

- **SSVEP are signals that are natural responses to visual stimulation at specific frequencies. When the retina is excited by a visual stimulus ranging from 3.5 Hz to 75 Hz, the brain generates electrical activity at the same (or multiples of) frequency of the visual stimulus.**
- **Excellent signal-to-noise ratio and relative immunity to artifacts.**
- **Applications:**
  - **SSVEP-controlled robots (Boston University)**
  - **User-friendly interface**



P300 ← ERP

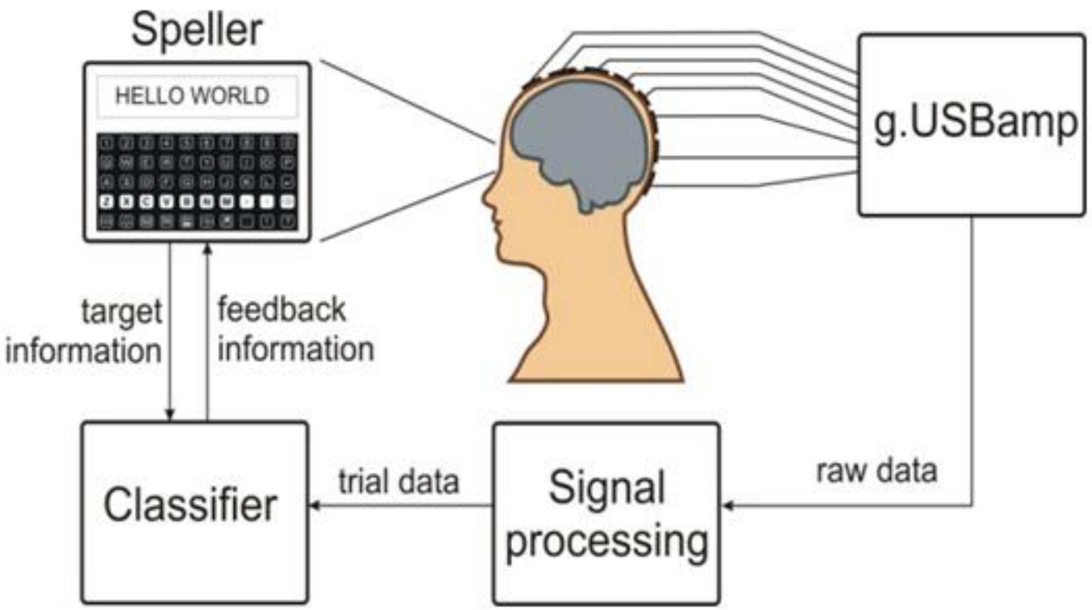
- **P300 is thought to reflect processes involved in stimulus evaluation or categorization.**
- **It is usually elicited using the oddball paradigm in which low-probability target items are inter-mixed with high-probability non-target (or "standard") items.**
- **Results in a positive curve on EEG after 300ms.**
- **Strongest signal at parietal lobe.**



- 6x6 matrix of symbols
- Subject concentrates on a symbol (i.e. cell)
- Each row and column flashes twice
  - i.e., 2 target flashes vs. 10 non-target flashes
  - random order
  - for very short time (e.g. 100 ms)

P300

- **(Farwell and Donchin 1988)**
- **95% accuracy at 1 character per 26s**

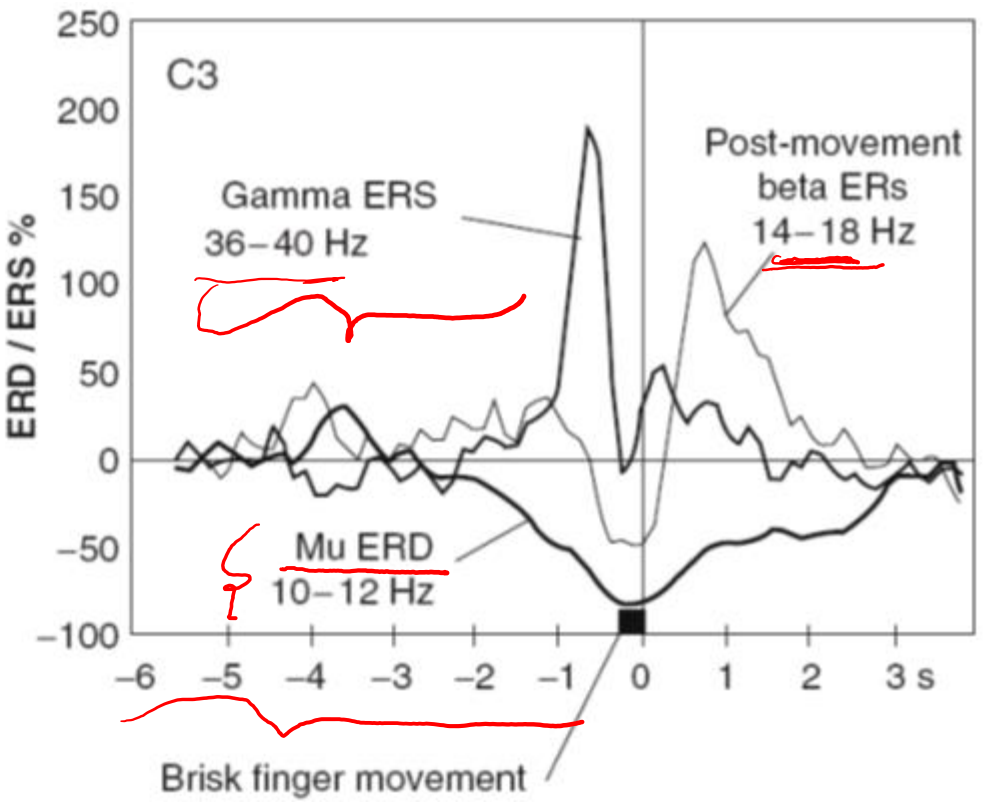


ERS/ERD

- **Event-related desynchronization (ERD) and event-related synchronization (ERS) is the change of signal's power occurring in a given band relative to a reference interval.**
- **People have naturally occurred brain rhythms over areas of the brain concerned with touch and movement. When people imagine moving, these brain rhythms first become weaker, then stronger. These two changes are called ERD and ERS, respectively.**
- **ERS**
  - oscillatory power increase
  - associated with activity decrease
- **ERD**
  - oscillatory power decrease
  - associated with activity increase

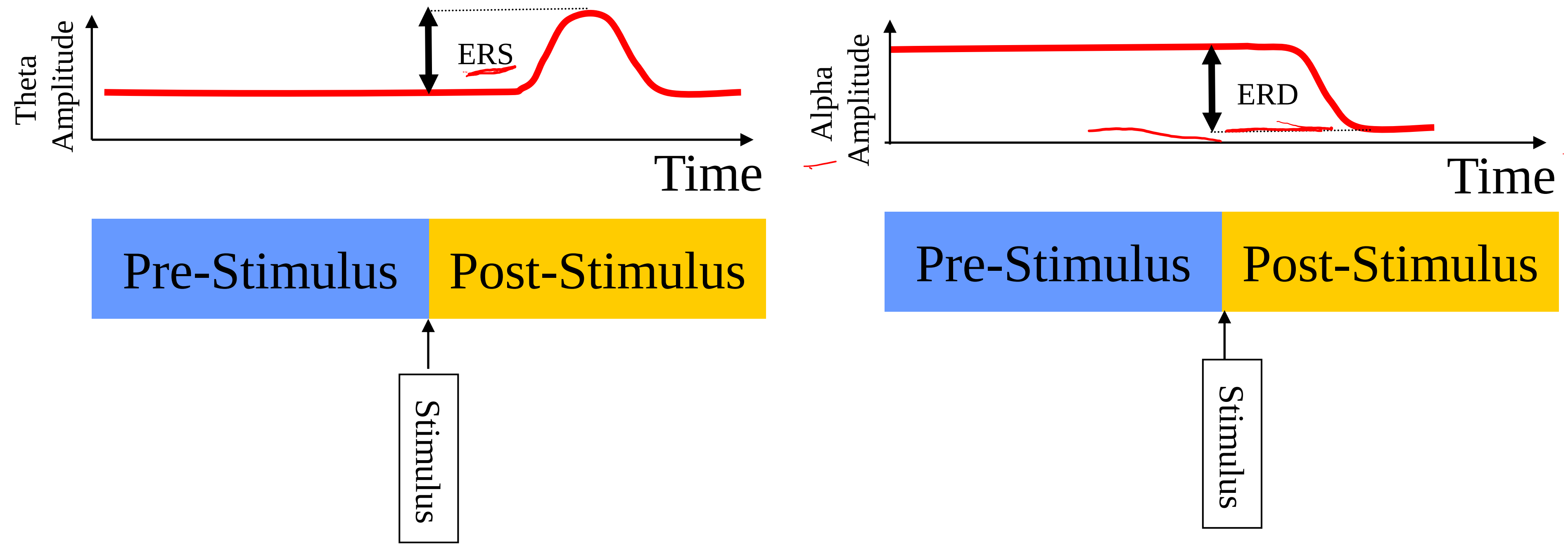
ERS/ERD

- **The imagination of either a left or right hand movement results in:**
  - **An amplitude attenuation (Event-Related Desynchronization (ERD)) of μ (8-12Hz) and central beta EEG-rhythms (13-30Hz) at the contralateral sensorial motor representation area and,**
  - **in some cases, in an amplitude increase (Event-Related Synchronization (ERS)) within the γ-band (30-40Hz) at the ipsi-lateral hemisphere(6).**

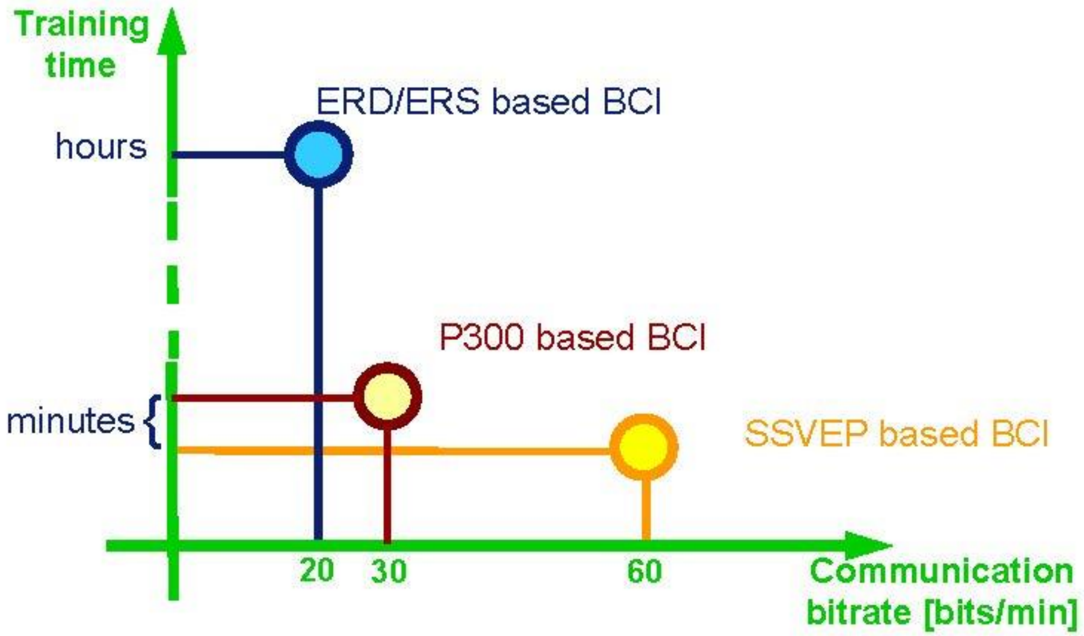


EEG recorded from C3 electrode.

4 - 8 Hz
8-13 Hz


Theta Amplitude
ERS
Time
Pre-Stimulus
Post-Stimulus
Stimulus
Alpha Amplitude
ERD
Time
Pre-Stimulus
Post-Stimulus
Stimulus

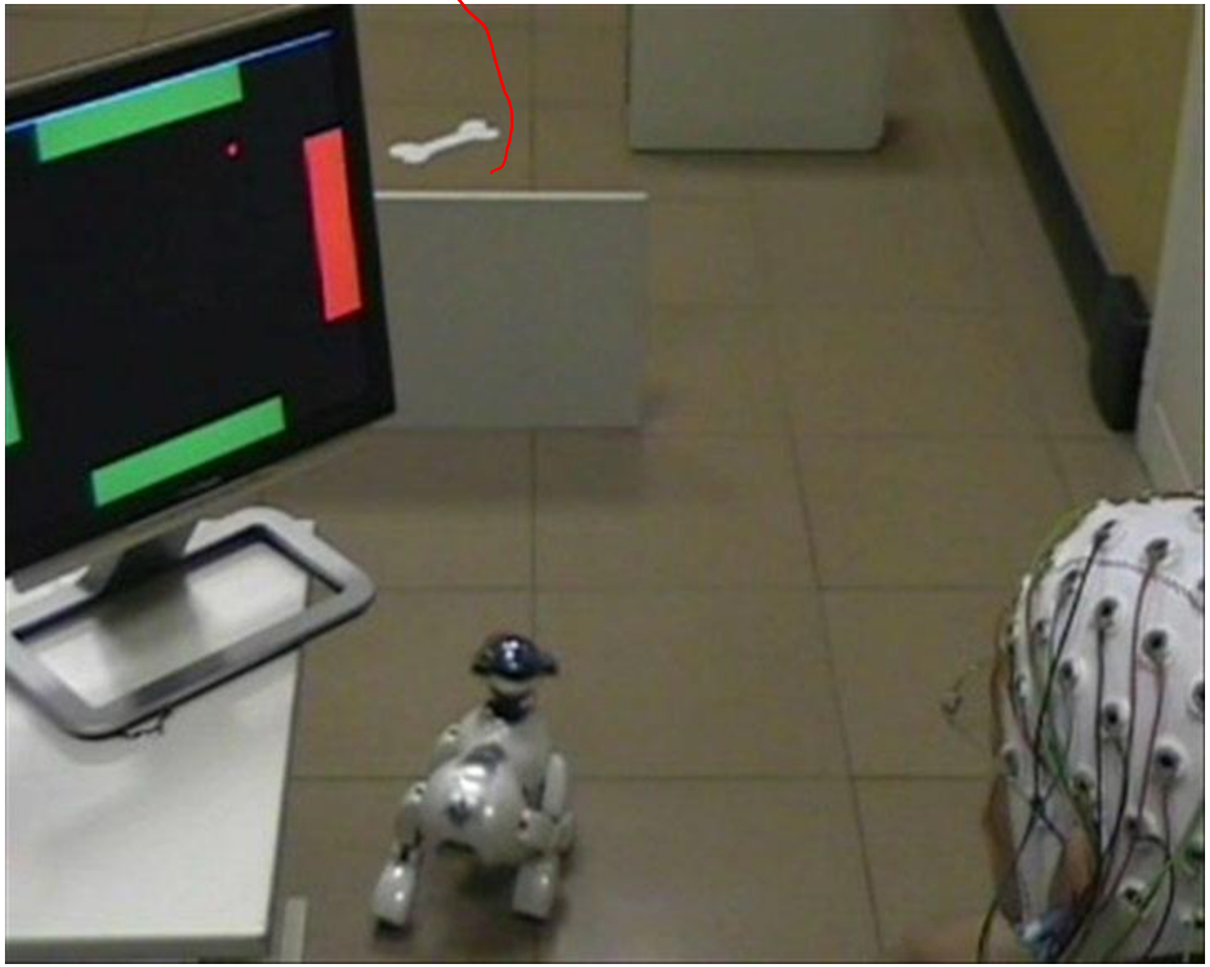
Communication Issues



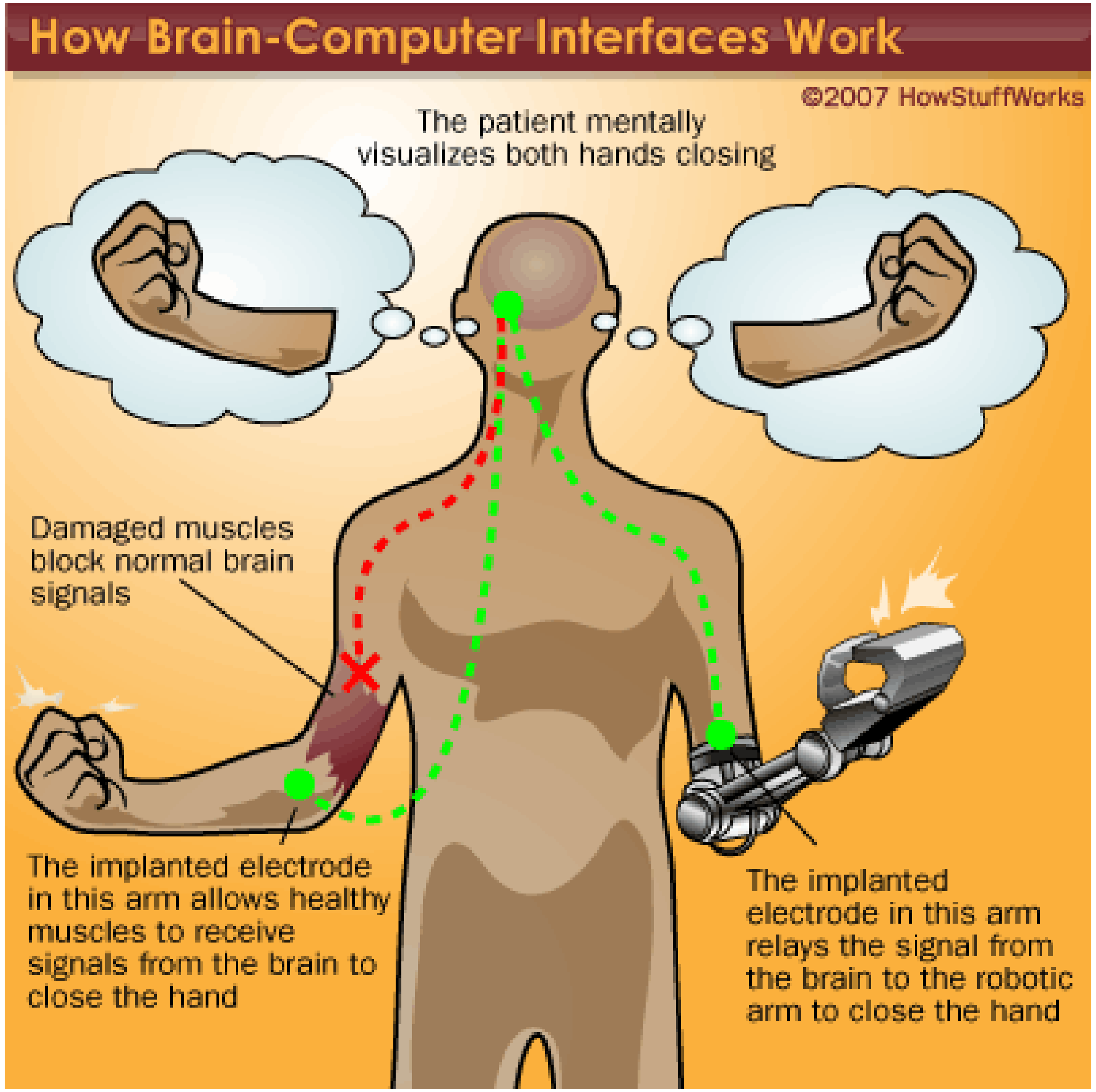
Typical training time versus communication bitrate for the three main types of noninvasive EEG based BCIs.

BCI Applications

BCI – operated robot

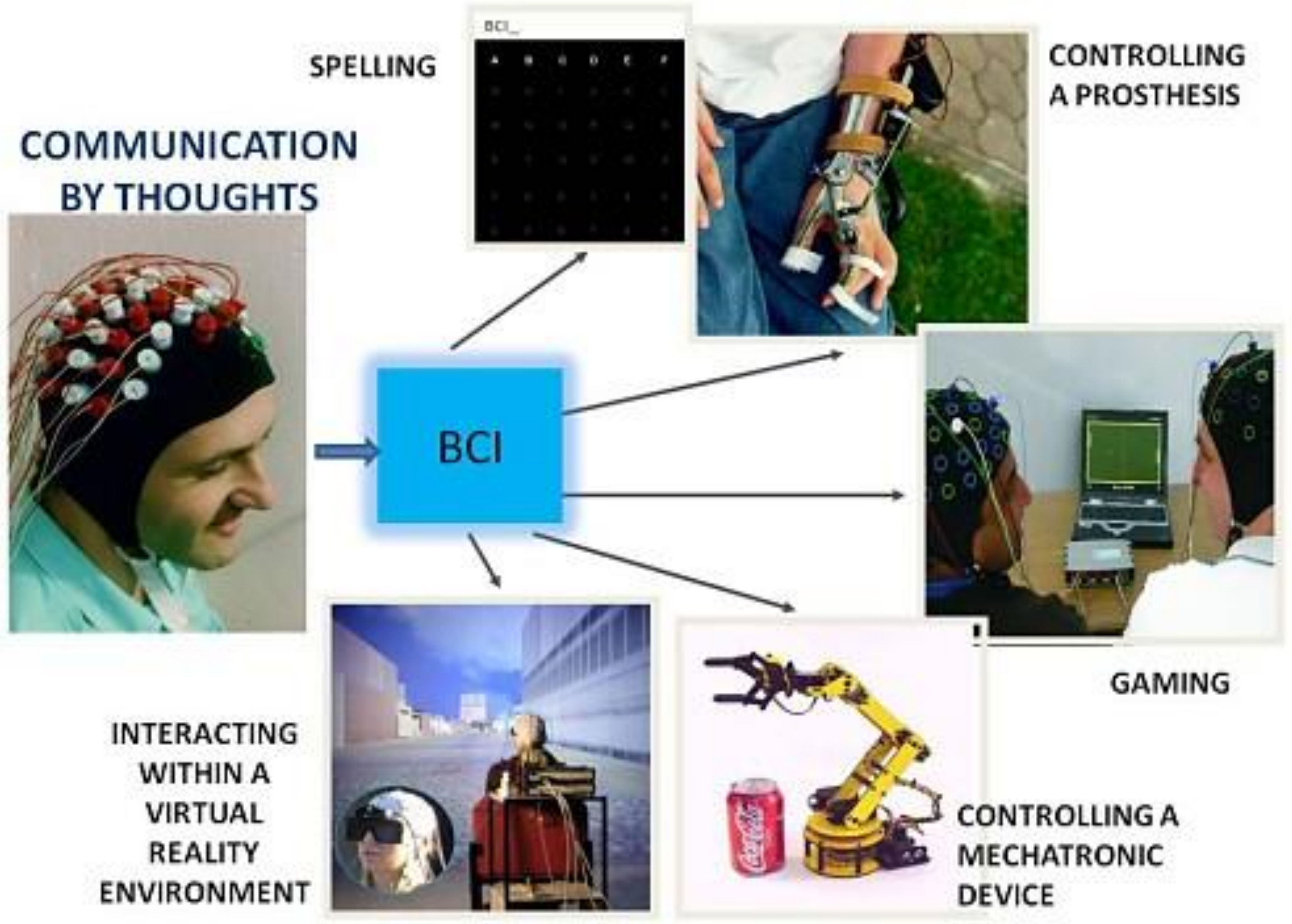


BCI Applications



BCI Applications

BCI Applications



Thank you!

EEG Variables

Course Instructor

Dr. Annushree Bablani

Acknowledgments: **Dr. Sreeja S R**

EEG

- Electroencephalogram (EEG) signals are useful for diagnosing various mental conditions such as epilepsy, memory impairments and sleep disorders.
- EEGs can indicate the general conscious state of a person, e.g., asleep, awake, anaesthetized, since each state is correlated with particular EEG patterns.
- A flat EEG (no electrical activity) is clinical evidence of death.

Why EEG?

- Hardware costs are significantly lower than those of most other techniques.
- EEG sensors can be used in more places than fMRI, SPECT, PET, MRS, or MEG, as these techniques require bulky and immobile equipment.
- EEG has very high temporal resolution, on the order of milliseconds rather than seconds, commonly recorded at sampling rates between 250 and 2000 Hz thus a valuable tool for research and diagnosis.
- EEG is relatively tolerant of subject movement, unlike most other neuro imaging techniques. There even exist methods for minimizing, and even eliminating movement artifacts in EEG data.
- EEG is silent, which allows for better study of the responses to auditory stimuli.
- EEG does not involve exposure to high-intensity (>1 Tesla) magnetic fields, as in some of the other techniques, especially MRI and MRS. These can cause a variety of undesirable issues with the data, and also prohibit use of these techniques with participants that have metal implants in their body, such as metal-containing pacemaker.
- EEG can be used in subjects who are incapable of making a motor response.
- EEG is a powerful tool for tracking brain changes during different phases of life. EEG sleep analysis can indicate significant aspects of the timing of brain development, including evaluating adolescent brain maturation.

EEG Disadvantages

- Low spatial resolution on the scalp. fMRI, for example, can directly display areas of the brain that are active, while EEG requires intense interpretation just to hypothesize what areas are activated by a particular response.
- EEG poorly determines neural activity that occurs below the upper layers of the brain (the cortex).
- Unlike PET and MRS, cannot identify specific locations in the brain at which various neurotransmitters, drugs, etc. can be found.
- Often takes a long time to connect a subject to EEG, as it requires precise placement of dozens of electrodes around the head and the use of various gels, saline solutions, and/or pastes to keep them in place. Where as a general rule it takes considerably less time to prepare a subject for MEG, fMRI, MRS, and PET.

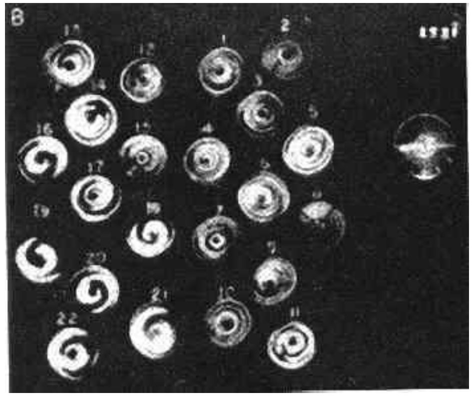
EEG Pioneers

In 1929, Hans Berger

- Recorded brain activity from the closed skull
- Reported brain activity changes according to the functional state of the brain
  - Sleep
  - Hypnothesis
  - Pathological states (epilepsy)

In 1957, Gray Walter

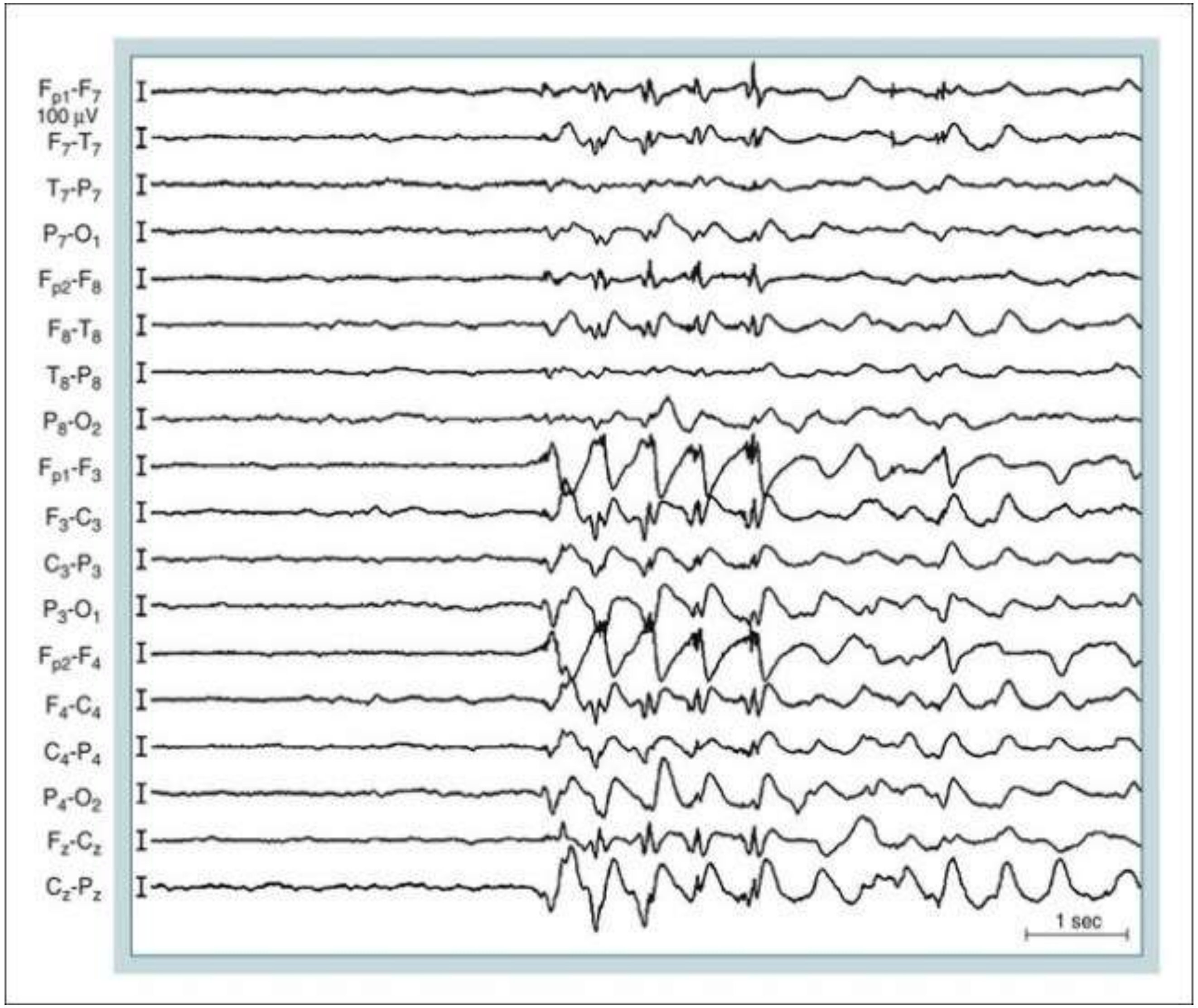
- Makes recordings with large numbers of electrodes
- Visualizes brain activity with the toposcope
- Shows that brain rhythms change according to the mental task demanded



Representation of EEG channels:

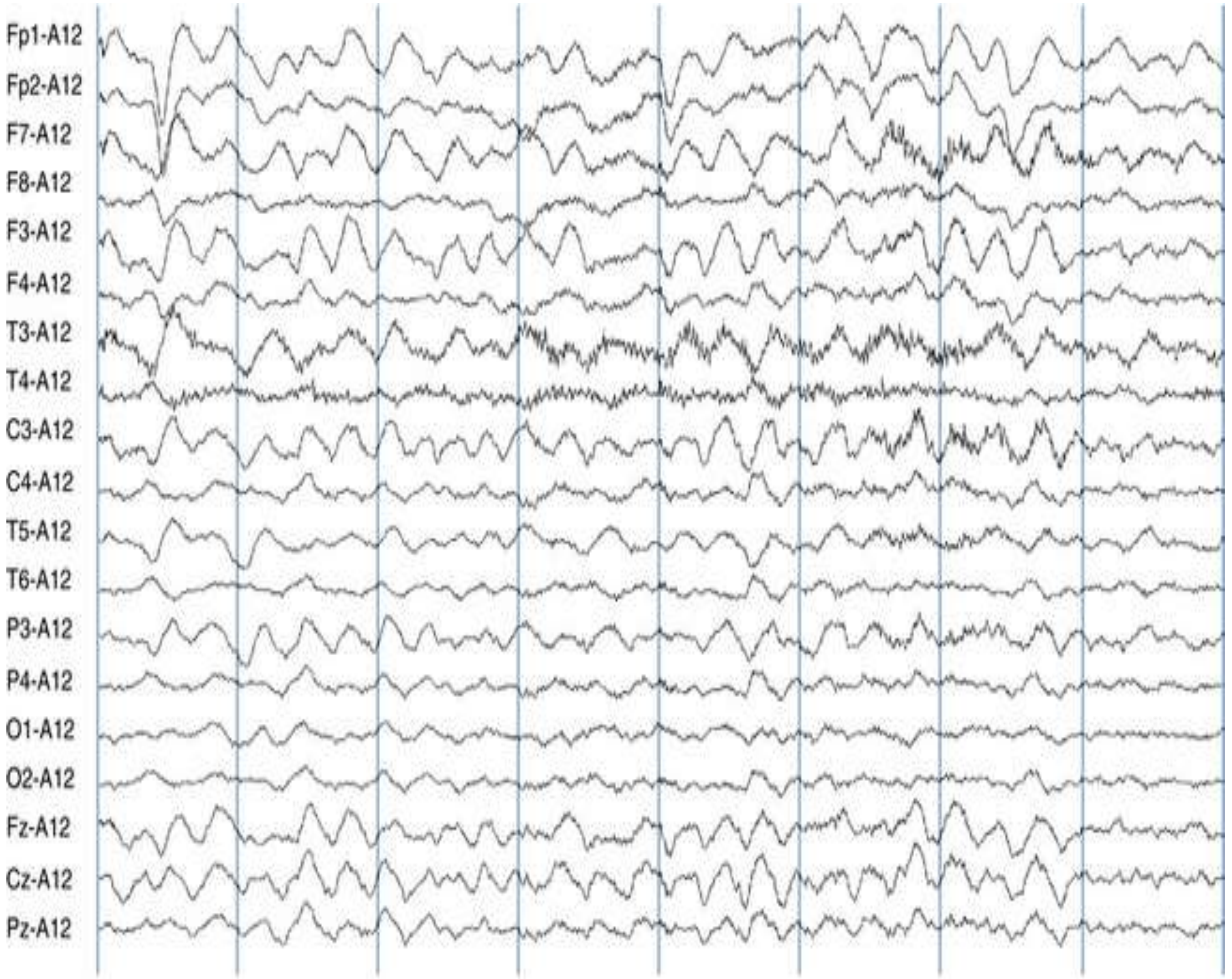
The representation of the EEG channels (i.e., waveform) is referred to as a **montage**.

- **Sequential montage**: Each channel represents the difference between two adjacent electrodes. The entire montage consists of a series of these channels. For example, the channel "Fp1-F3" represents the difference in voltage between the Fp1 electrode and the F3 electrode. The next channel in the montage, "F3-C3," represents the voltage difference between F3 and C3, and so on through the entire array of electrodes.



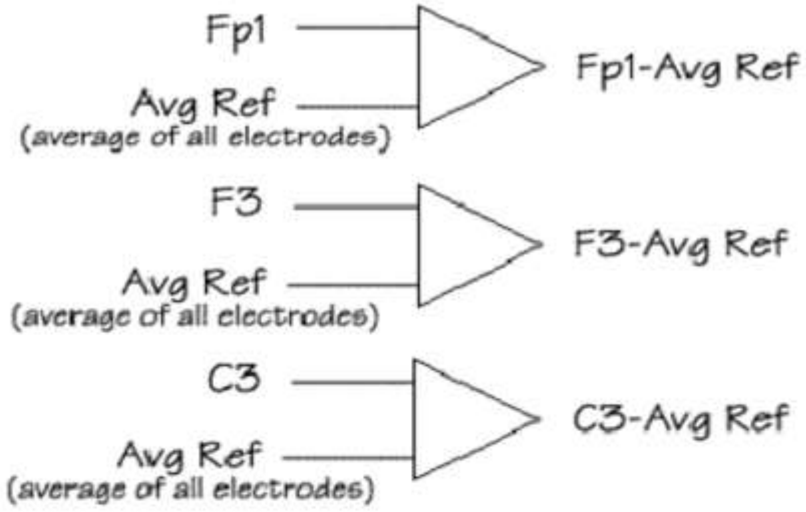
Representation of EEG channels:

- **Referential montage**: Each channel represents the difference between a certain electrode and a designated reference electrode. There is no standard position for this reference; it is, however, at a different position than the "recording" electrodes. Midline positions are often used because they do not amplify the signal in one hemisphere vs. the other. Another popular reference is "linked ears," which is a physical or mathematical average of electrodes attached to both earlobes or mastoids.

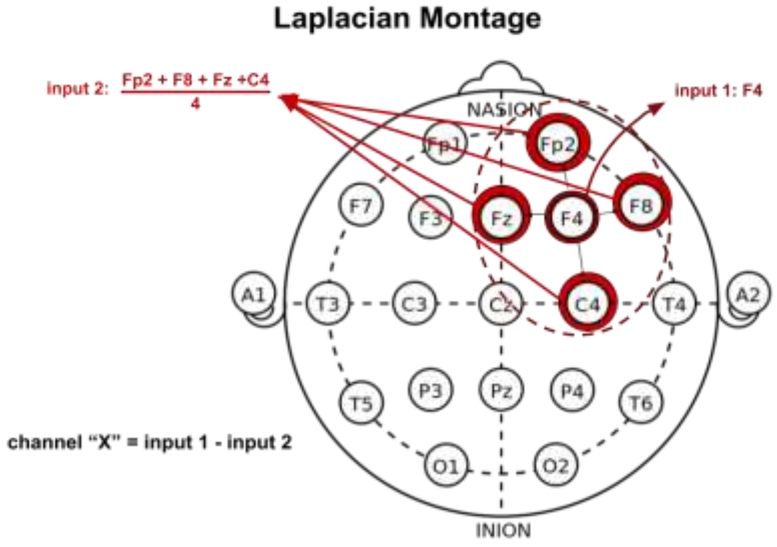


Representation of EEG channels:

- **Average reference montage:** The outputs of all of the amplifiers are summed and averaged, and this averaged signal is used as the common reference for each channel.



- **Laplacian montage:** Each channel represents the difference between an electrode and a weighted average of the surrounding electrodes.



EEG Rhythms

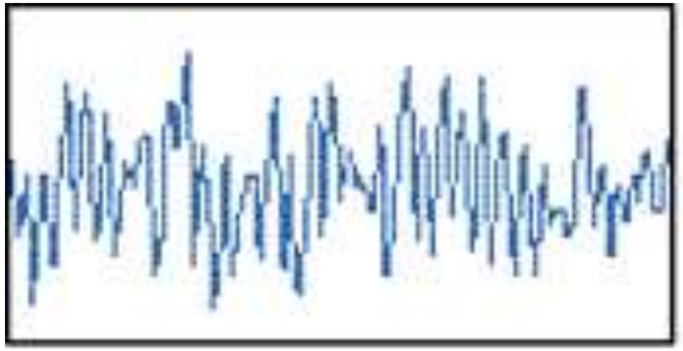
- Generally grouped by frequency: (amplitudes are about 100μV max)

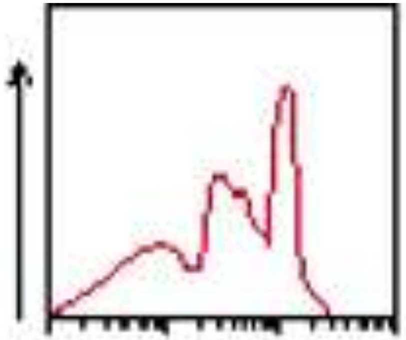
Type	Frequency	Location	Use
Delta	<4 Hz	everywhere	occur during sleep, coma
Theta	4-7 Hz	temporal and parietal	correlated with emotional stress (frustration & disappointment)
Alpha	8-15 Hz	occipital and parietal	reduce amplitude with sensory stimulation or **mental imagery**
Beta	16-30 Hz	parietal and frontal	can increase amplitude during intense **mental activity**
Gamma	>30 Hz	Somatosensory cortex	A decrease in gamma-band activity is associated with **cognitive decline**
Mu	8-12 Hz	frontal (motor cortex)	diminishes with movement or **intention of movement**
Lambda	sharp, jagged	occipital	correlated with visual attention
Vertex			higher incidence in patients with epilepsy or encephalopathy

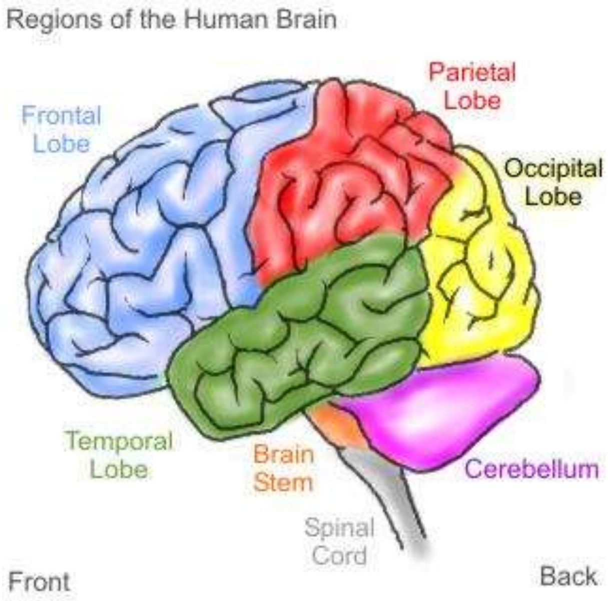
Alpha Rhythm

Frequency:	8 – 15 Hz
Amplitude:	5 – 100 microVolt
Location:	Occipital, Parietal
State of Mind:	Alert Restfulness
Source:	Oscillating thalamic pacemaker neurons

Alpha blockade occurs when new stimulus is processed







Beta Rhythm

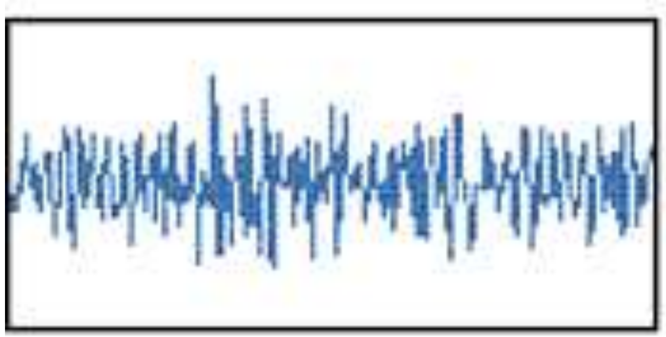
Frequency: 16 – 30 Hz

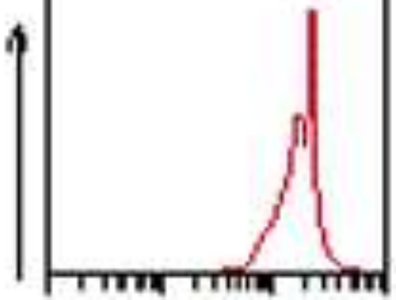
Amplitude: 2 – 20 microVolt

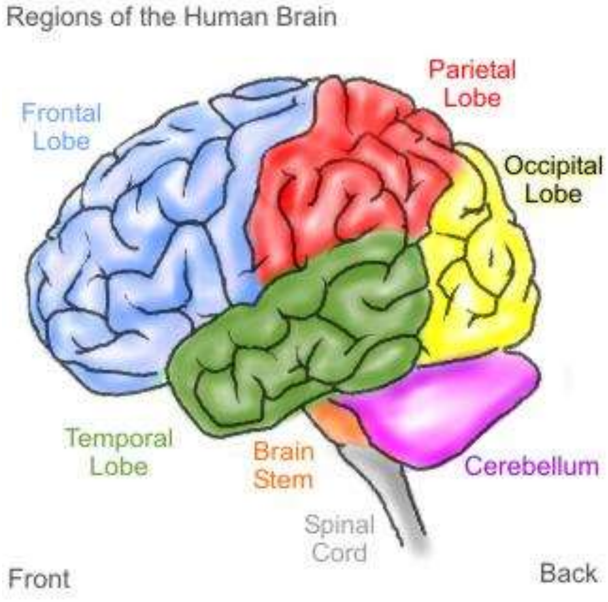
Location: Frontal

State of Mind: Mental Activity

Reflects specific information processing between cortex and thalamus







Delta Rhythm

Frequency: 1 – 4 Hz

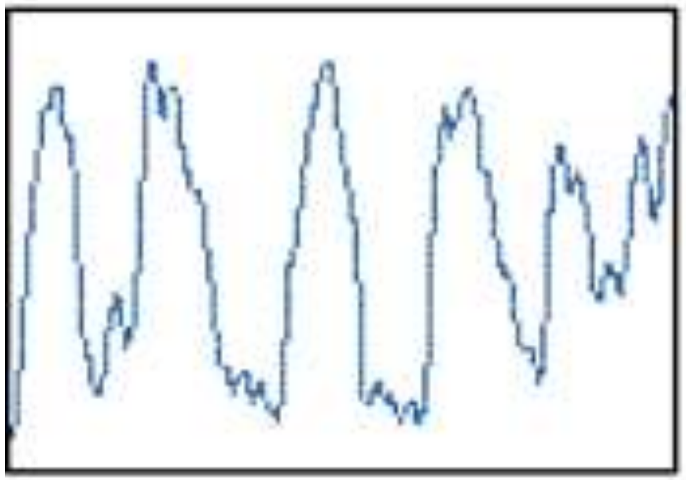
Amplitude: 20 – 200 microVolt

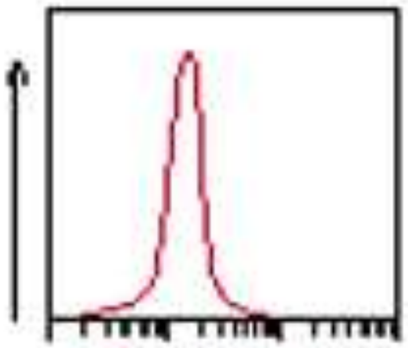
Location: Variable

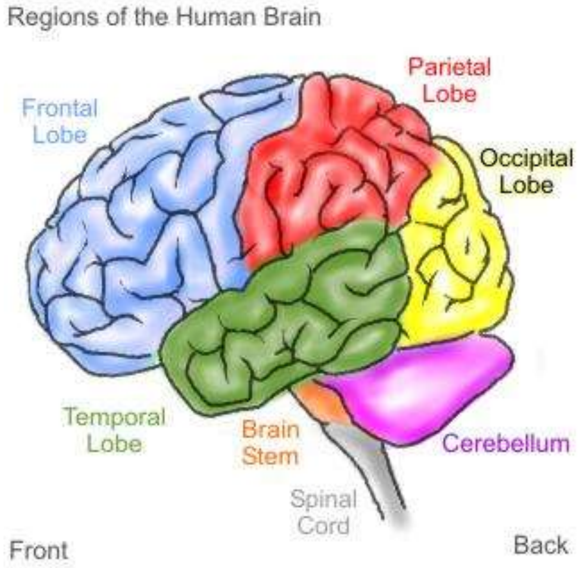
State of Mind: Deep sleep

Oscillations in Thalamus and deep cortical layers

Usually inibited by ARAS (Ascending Reticular Activation System)

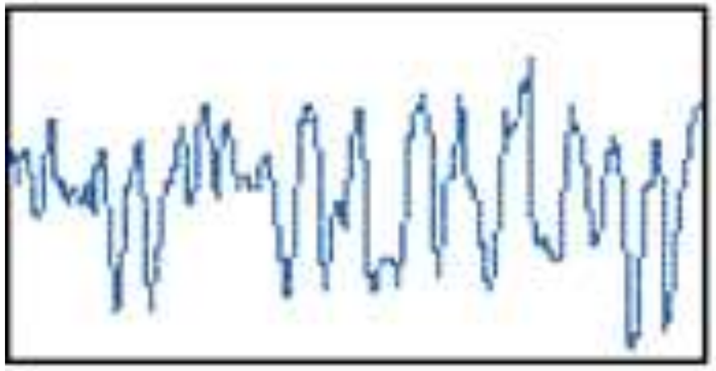


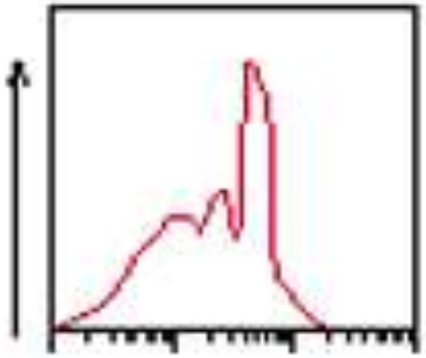


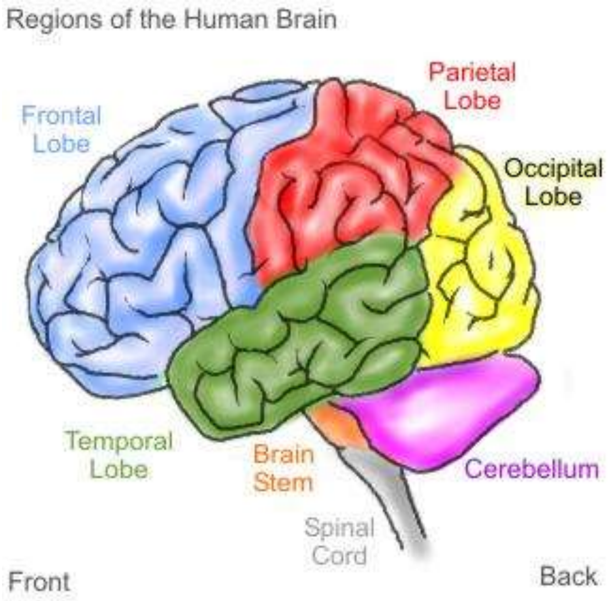


Theta Rhythm

Frequency:	4 – 7 Hz
Amplitude:	5 – 100 microVolt
Location:	Frontal, Temporal
State of Mind:	Sleepiness







Mu Waves

- Studied since 1930s
- Found in Motor Cortex
- Amplitude suppressed by Physical Movements, or *intent to* move physically
- (Wolpaw, et al 1991) trained subjects to control the mu rhythm by visualizing motor tasks to move a cursor up and down (1D)
- (Wolpaw and McFarland 2004) used a linear combination of Mu and Beta waves to control a 2D cursor.
- Weights were learned from the users in real time.
- Cursor moved every 50ms (20 Hz)
- 92% “hit rate” in average 1.9 sec

Alpha and Beta Waves

- Studied since 1920s
- Found in Parietal and Frontal Cortex
- Relaxed - Alpha has high amplitude
- Excited - Beta has high amplitude
- So, Relaxed -> Excited

  means Alpha -> Beta

Variables used in EEG measurement:

Frequency:

- Frequency refers to rhythmic repetitive activity (in Hz). The frequency of EEG activity can have different properties including:
- **Rhythmic**. EEG activity consisting in waves of approximately constant frequency.
- **Arrhythmic**. EEG activity in which no stable rhythms are present.
- **Dysrhythmic**. Rhythms and/or patterns of EEG activity that characteristically appear in patient groups or rarely seen in healthy subjects.

Variables used in EEG measurement:

Voltage: Voltage refers to the average voltage or peak voltage of EEG activity.

- **Attenuation** (synonyms: suppression, depression). Reduction of amplitude of EEG activity resulting from decreased voltage.
- **Hypersynchrony**. Seen as an increase in voltage and regularity of rhythmic activity, or within the alpha, beta, or theta range. The term implies an increase in the number of neural elements contributing to the rhythm.
- **Paroxysmal**. Activity that reaching (usually) quite high voltage and ending with an abrupt return to lower voltage activity. Though the term does not directly imply abnormality, much abnormal activity is paroxysmal.

Variables used in EEG measurement:

Morphology: Morphology refers to the shape of the waveform. The shape of a wave or an EEG pattern is determined by the frequencies that combine to make up the waveform and by their phase and voltage relationships. Wave patterns can be described as being:

- **Monomorphic**. Distinct EEG activity appearing to be composed of one dominant activity
- **Polymorphic**. Distinct EEG activity composed of multiple frequencies that combine to form a complex waveform.
- **Sinusoidal**. Waves resembling sine waves. Monomorphic activity usually is sinusoidal.
- **Transient**. An isolated wave or pattern that is distinctly different from background activity.
    - **Spike**: a transient with a pointed peak and duration from 20 to less than 70 msec.
    - **Sharp wave**: a transient with a pointed peak and duration of 70-200 msec.

Variables used in EEG measurement:

Synchrony:

- Synchrony refers to the simultaneous appearance of rhythmic or morphologically distinct patterns over different regions of the head, either on the same side (unilateral) or both sides (bilateral).

Periodicity:

- Periodicity refers to the distribution of patterns or elements in time (e.g., the appearance of a particular EEG activity at more or less regular intervals). The activity may be generalized, focal or lateralized.

Thank You!

EEG Artifacts

<u>Course Instructors</u>

Dr. Annushree Bablani

Acknowledgments: Dr. Sreeja S R

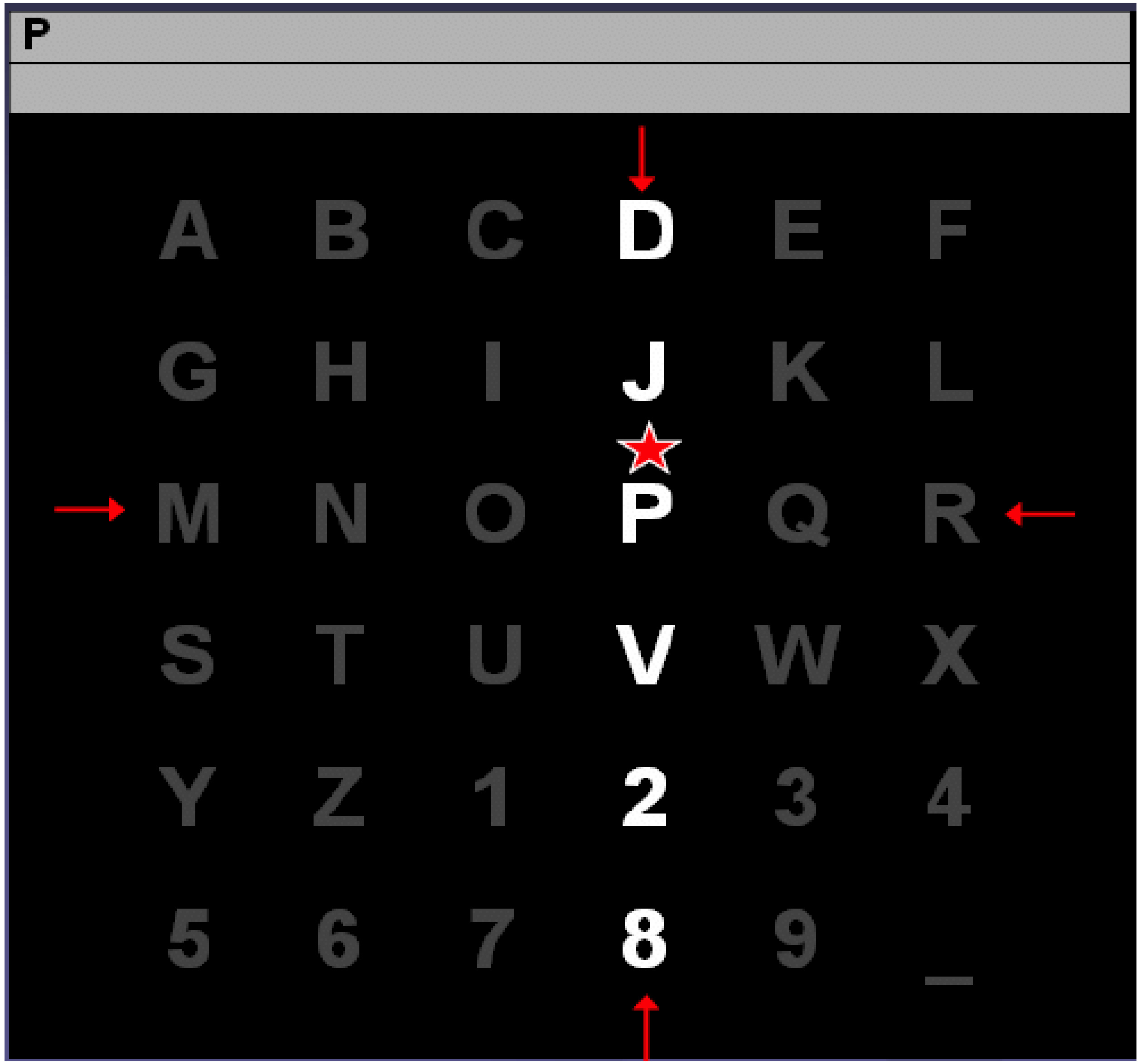
EEG Paradigms

01 P300

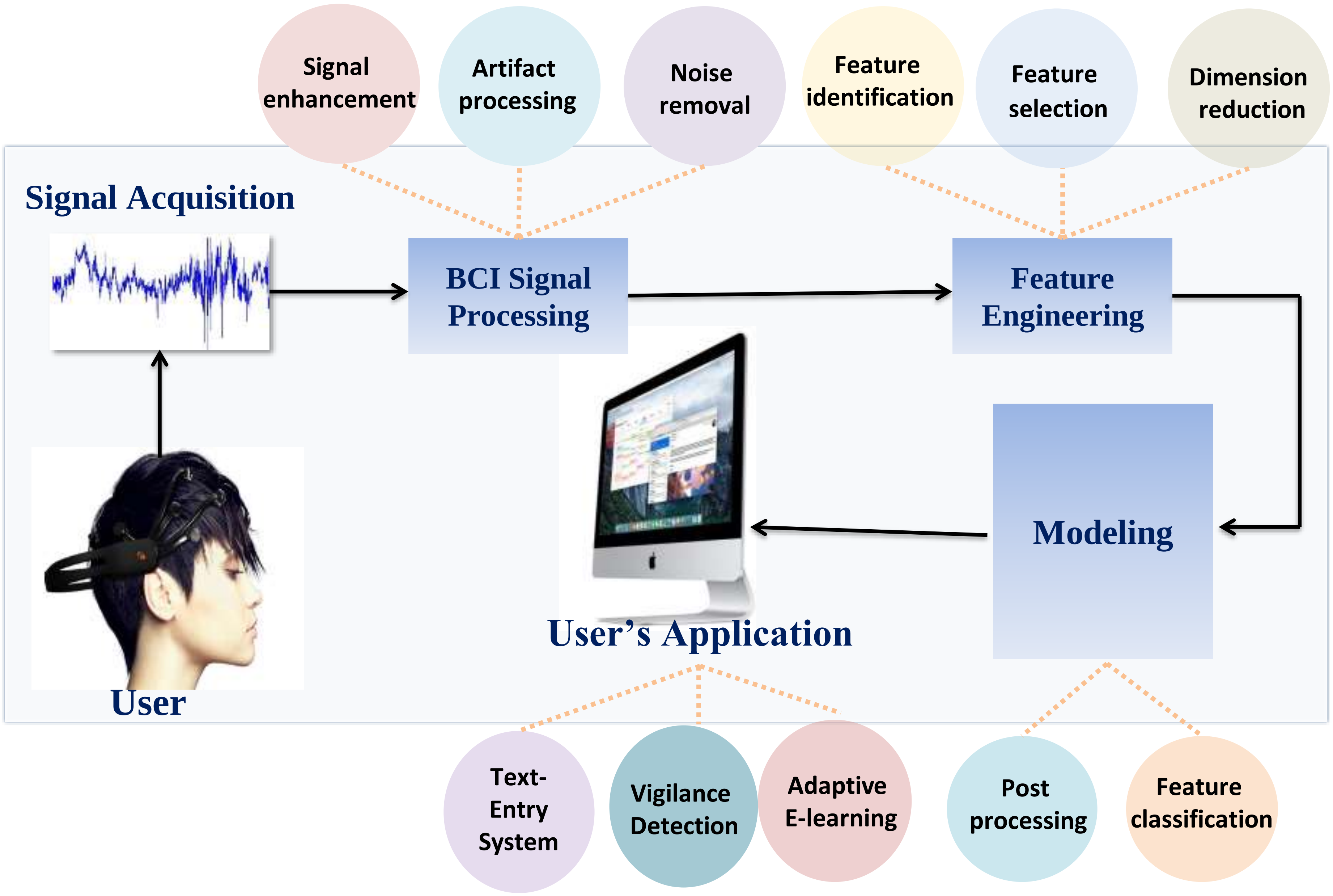
02 SCPs

03 SSVEPs

04 SMRs



EEG based BCI System Development



Recording the EEG

- **EEG electrodes**:
  - Small metal discs usually made of stainless steel, tin, gold or silver covered with a silver chloride coating.
  - They are placed on the scalp in spatial positions using the International 10/20 system.

Fig: EEG cables showing the disc electrodes to which electrode gel is applied and applied to the subject's scalp.

Recording the EEG

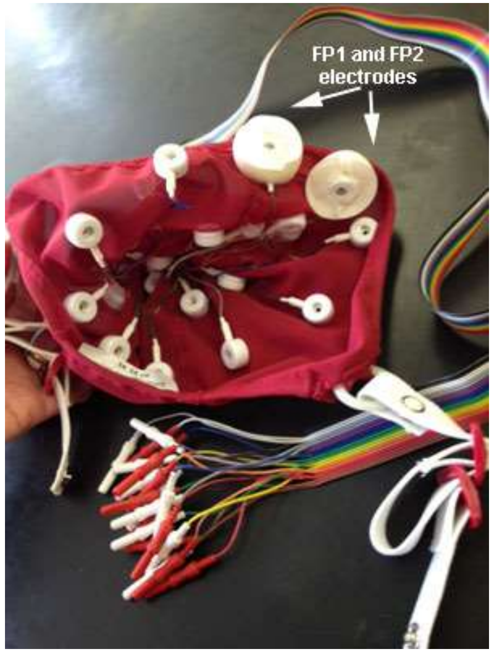


Fig: Many recording systems use a cap into which electrodes are embedded; this facilitates recordings when high density arrays of electrodes are needed or when comparing recording sites. The image to the right shows the inside of such a cap.

Recording the EEG

- **Electrode gel:**
  - It acts as a malleable extension of the electrode, so that the movement of the electrodes cables is less likely to produce artifacts.
  - The gel maximizes skin contact and allows for a low-resistance recording through the skin.
- **Impedance**
  - A measure of the impediment to the flow of alternating current, measured in ohms at a given frequency.
  - Larger numbers mean higher resistance to current flow.
  - The higher the impedance of the electrode, the smaller the amplitude of the EEG signal.
  - In EEG studies, should be at lest 100 ohms or less and no more than 5 kohm.

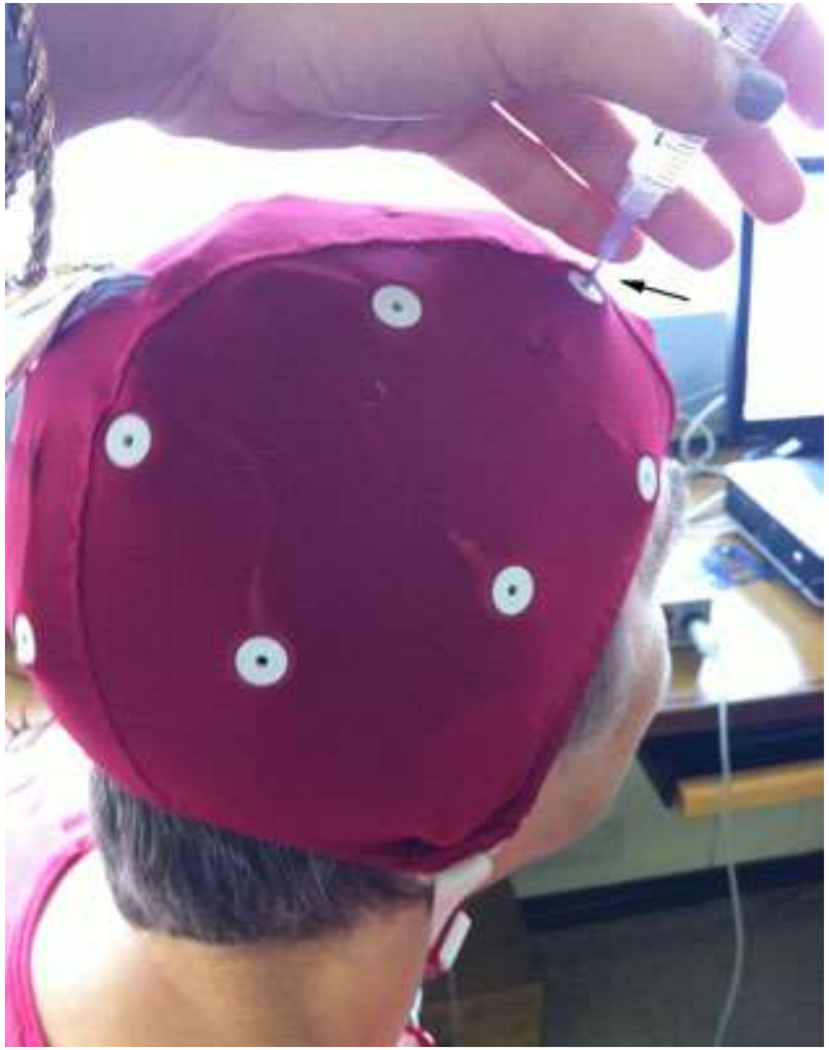


Fig: The electrolytic gel is injected into each cavity until a small amount comes out the hole in the mount. With a moderate amount of downward pressure, the syringe with a blunt needle is rapidly rocked back and forth.

EEG Artifacts

- The electrical artifacts that is not of cerebral origin.
- Anything that is NOT of cerebral origin is termed as **ARTIFACT**
- Physiological and Electrophysiological artifacts.
- Physiological – source (generated other than brain ie. Body)
- Electrophysiological – arise outside the body - equipment and environment
- Some readily distinguished, others closely resemble cerebral activity.

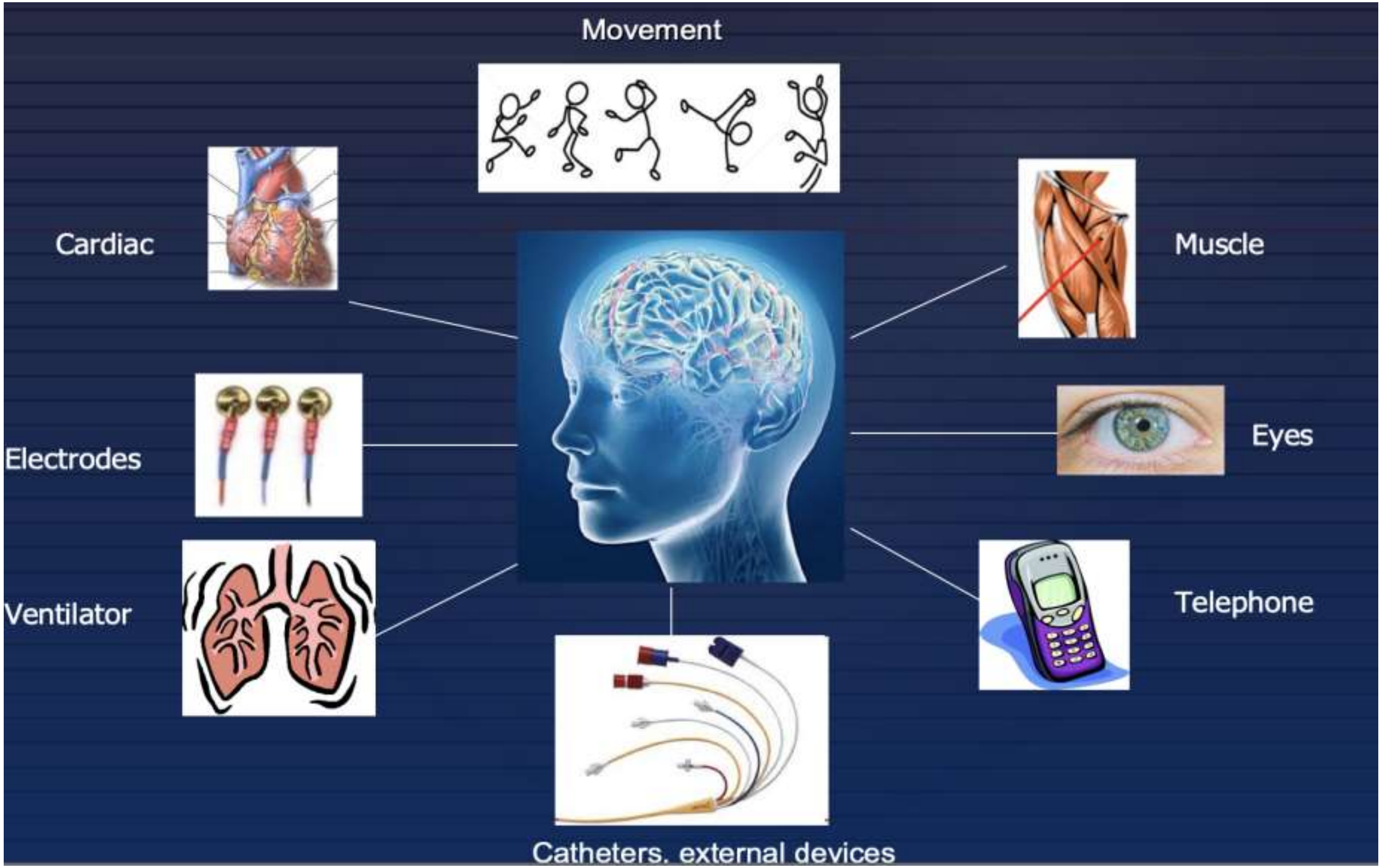
Principles to discriminate artifacts from EEG signals

- Physiological activity has a logical topographic field of distribution with an excepted fall of the voltage potentials
- Artifact have an illogical distribution that defies the principles of localization

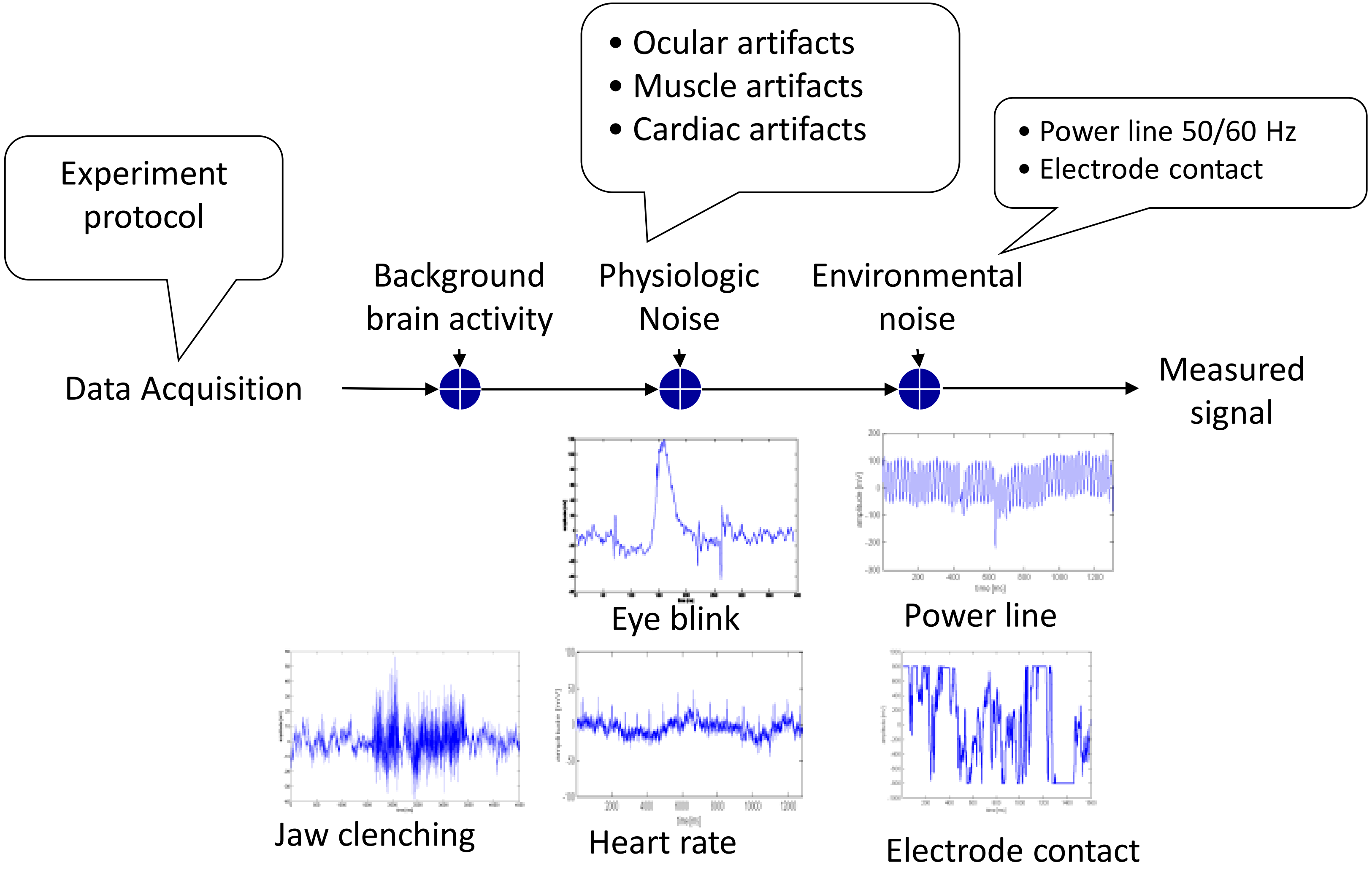
KEY TO AN ARTIFACT FREE RECORDING

- Good, clean preparation
- Good hook-up, neatly bundled electrodes
- Place jack-box close to patients head
- Keep the subject cool, not cold
- Unplug all electrical items close to patient, i.e. bed, radio, fan, etc.

EEG Artifacts

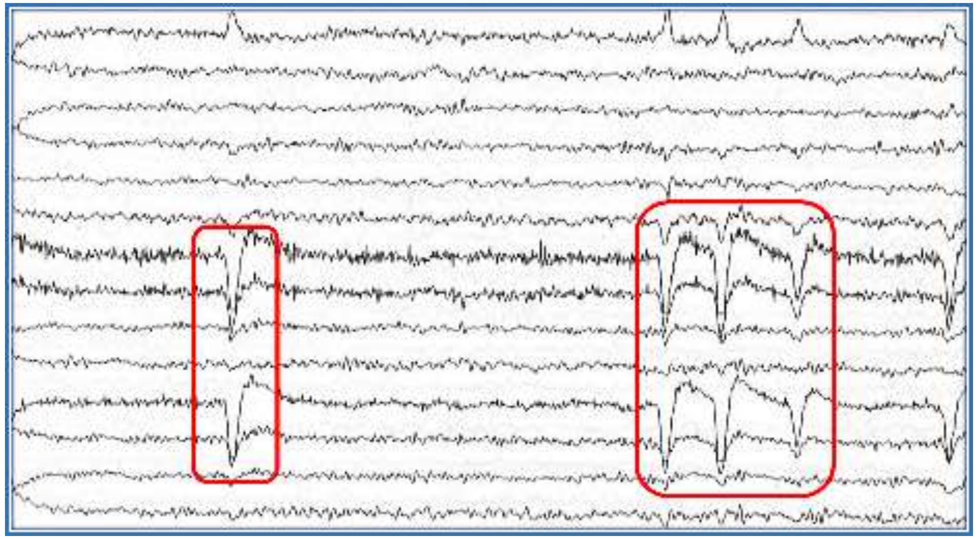


Captured EEG Signal

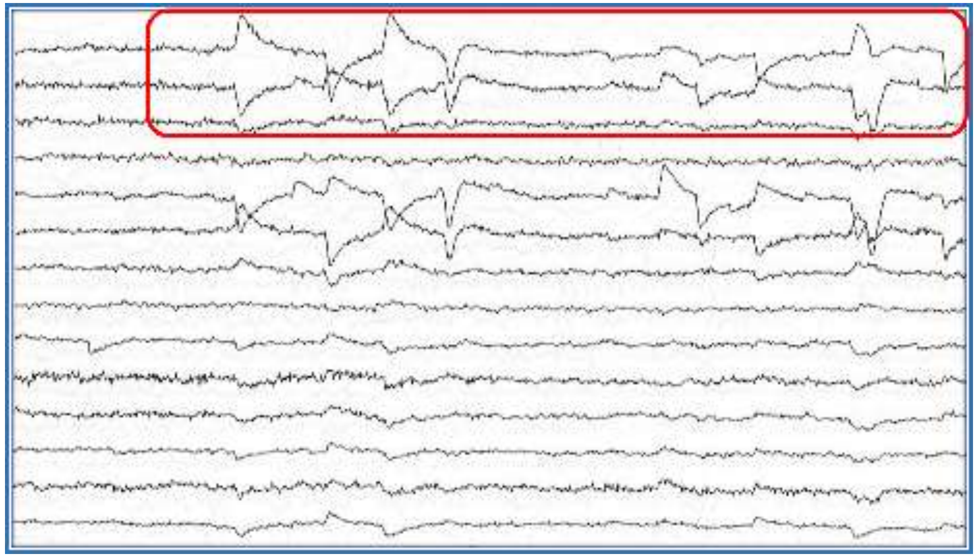


Ocular Artifacts

- Blinks
- Eye flutter
- Lateral gaze
- Slow/roving eye movement
- Rapid eye movement
- Electroretinogram (ERG)



Blink



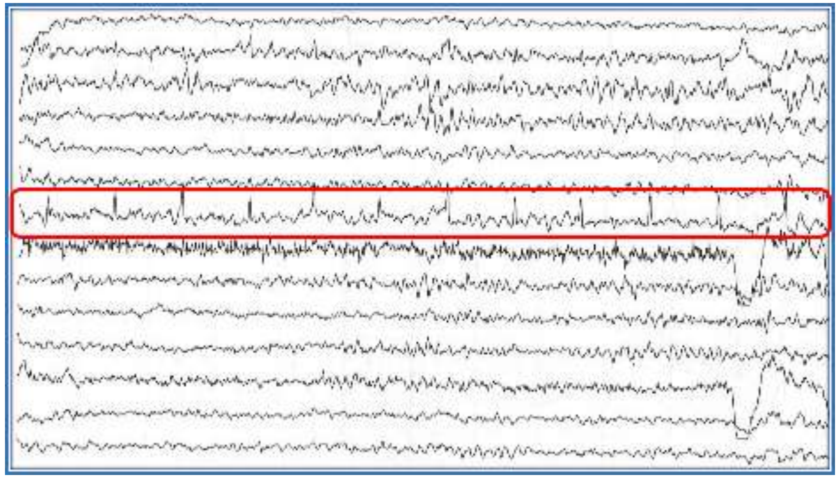
Lateral Eye Movement

Cardiac Artifacts

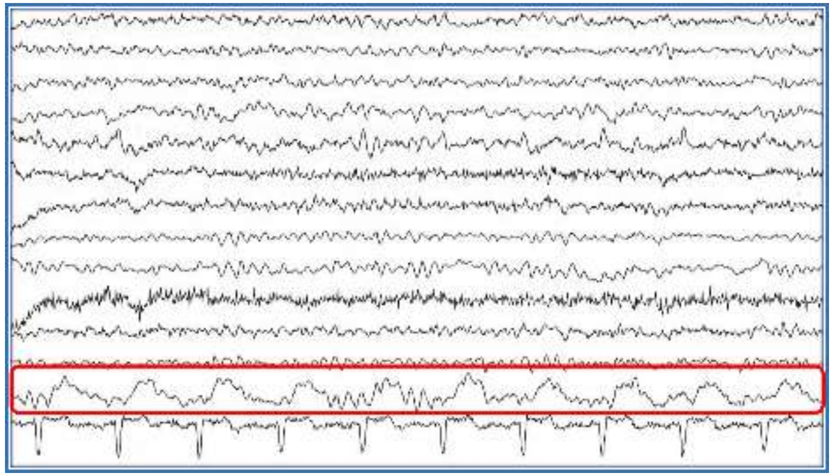
- Mechanical and Electrical
- ECG, Pacemaker - Electrical
- Pulse, Ballistocardiographic – Mechanical

✓ Mostly these are high in amplitude and prominent in babies, obese and short neck persons.

✓ Referential montages picks up cardiac artifacts.



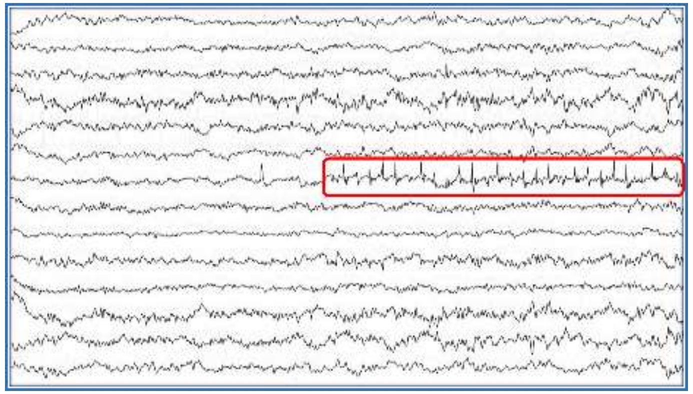
Cardiac (Electrical)



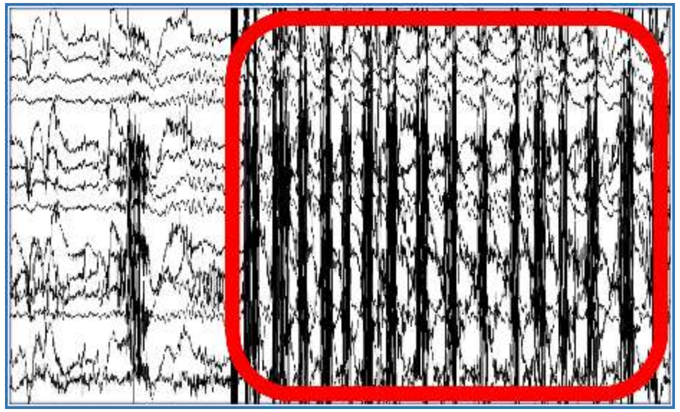
Cardiac (Mechanical)

Muscle Artifacts

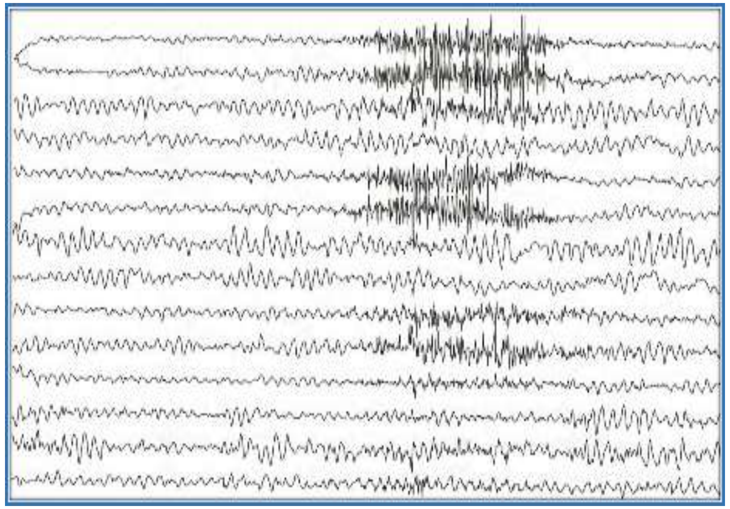
- ✓ Glossokenetic (related to tongue movements, Chew and swallow)
- ✓ Photomyogenic/ Photo-myoclonic (When flash of light falls over the face, the activity occurs due to myoclonus of the facial muscles).
- ✓ Surface EMG (Electromyography) – used to measure electrical activity during muscle contractions and relaxation cycles.



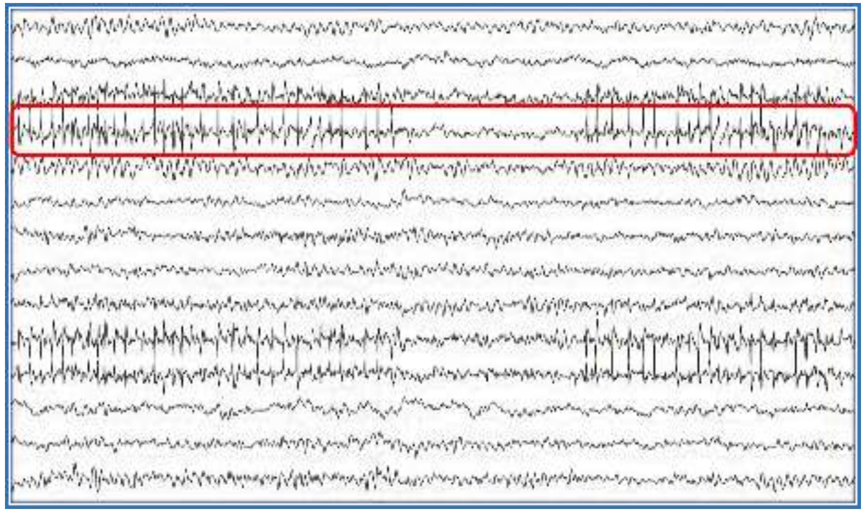
Photomyogenic



Chewing



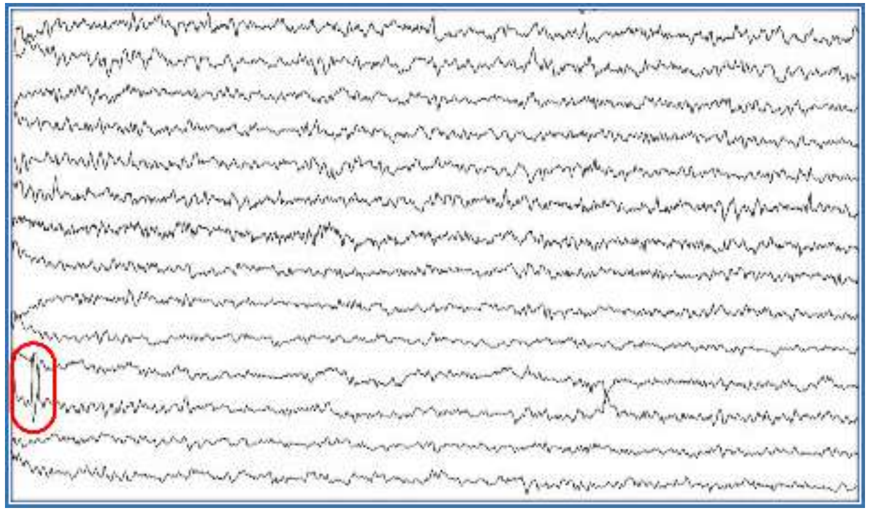
Electromyography (Scalp)



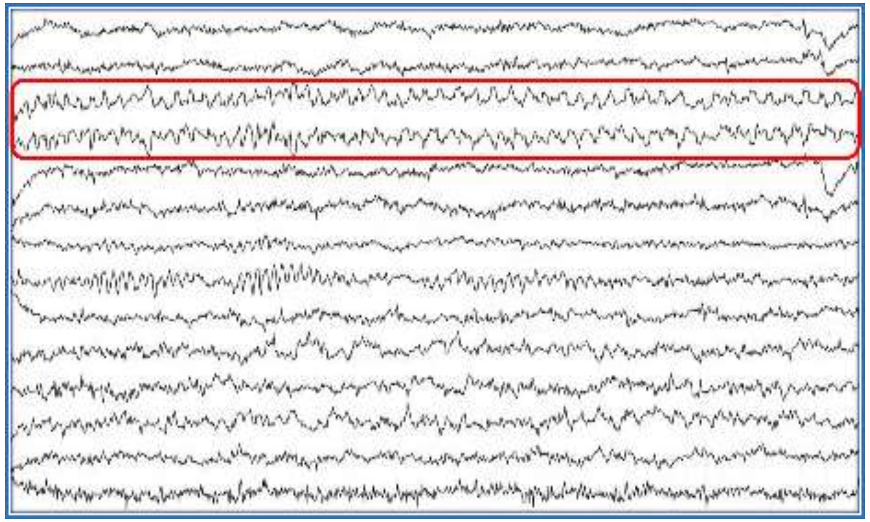
Electromyography (Facial)

Electrode and Equipment Artifacts

- ✓ Electrode pop, electrode contact, electrode movement
- ✓ Perspiration – the process of sweating
- ✓ salt bridge – differs from perspiration by low amplitude.
- ✓ Movement artifacts - Movement of head, body and limbs produce irregular high voltage potentials
- ✓ 50/60 Hz ambient electrical noise.
- ✓ Ventilators, circulatory pumps.
- ✓ Telephone, mobile.



Electrode Pop



Electrode Movement

Electrode and Equipment Artifacts

- Seen due to smearing of the electrode paste between electrodes or presence of perspiration across the scalp
- Forms an unwanted electrical connection between the electrodes forming a channel

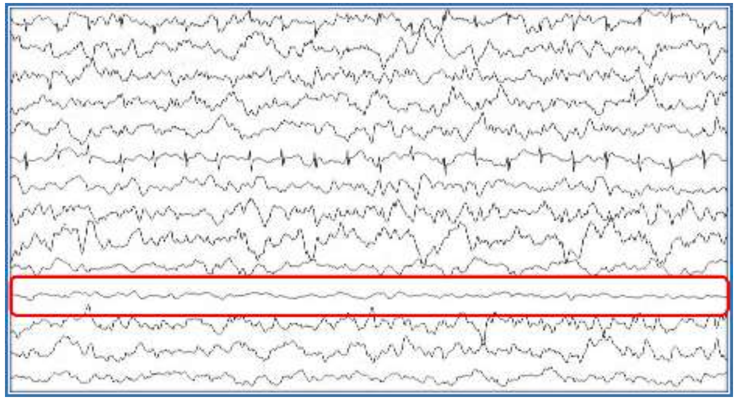
✓Perspiration artifact

- manifests as low amplitude
- undulating (smooth) waves
- duration is typically greater than 2 sec

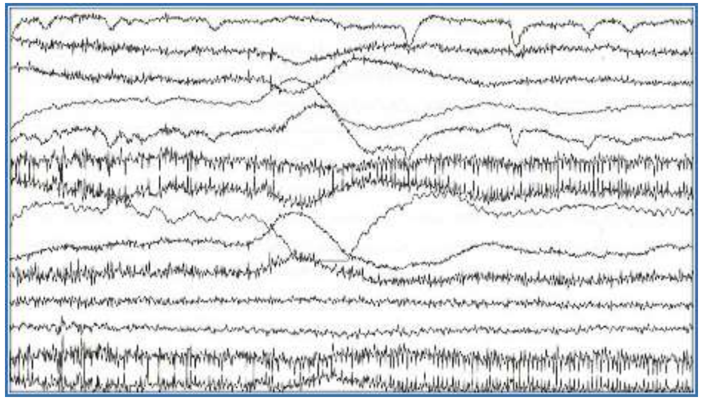
✓Slat bridge artifact

- lower in amplitude
- not wavering with low frequency oscillation - typically include only one channel
- It may appear flat and close to isoelectric

Electrode and Equipment Artifacts

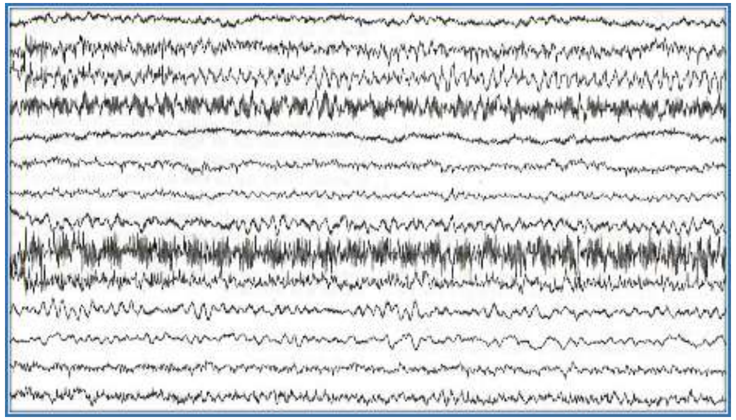


Salt Bridge

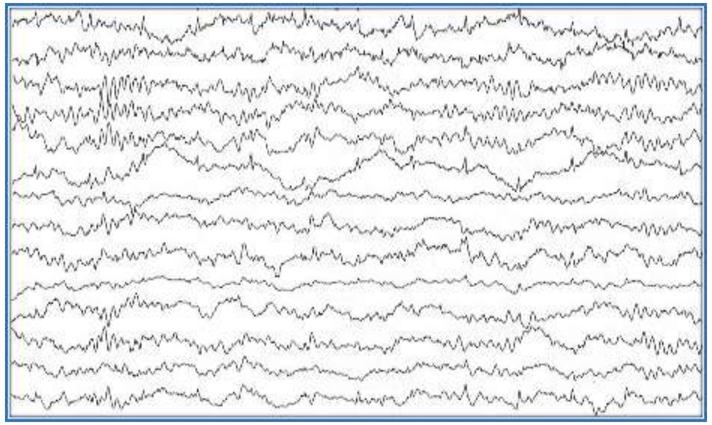


Electrode Lead Movement

Electrical Motor



60 Hz



Perspiration

Phone

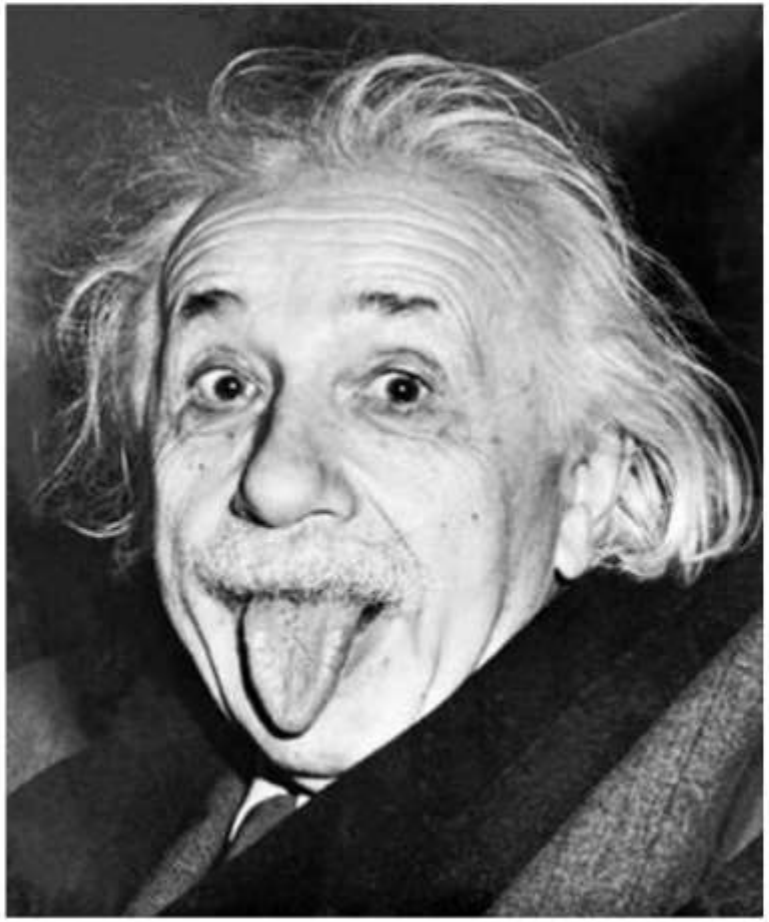
Thank You!

EEG Signal Pre-processing - Epoching

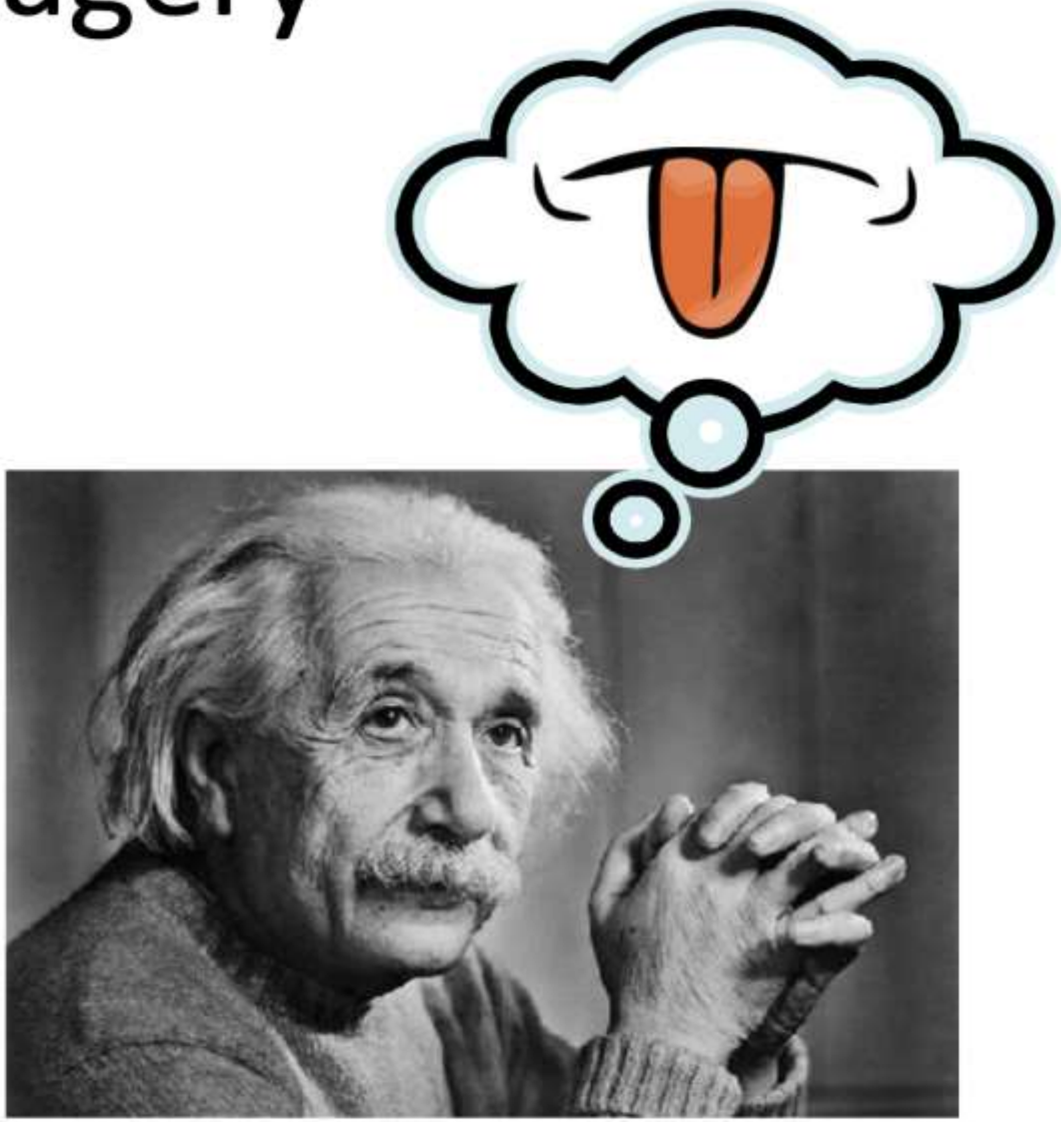
Course Instructor

Dr. Annushree Bablani

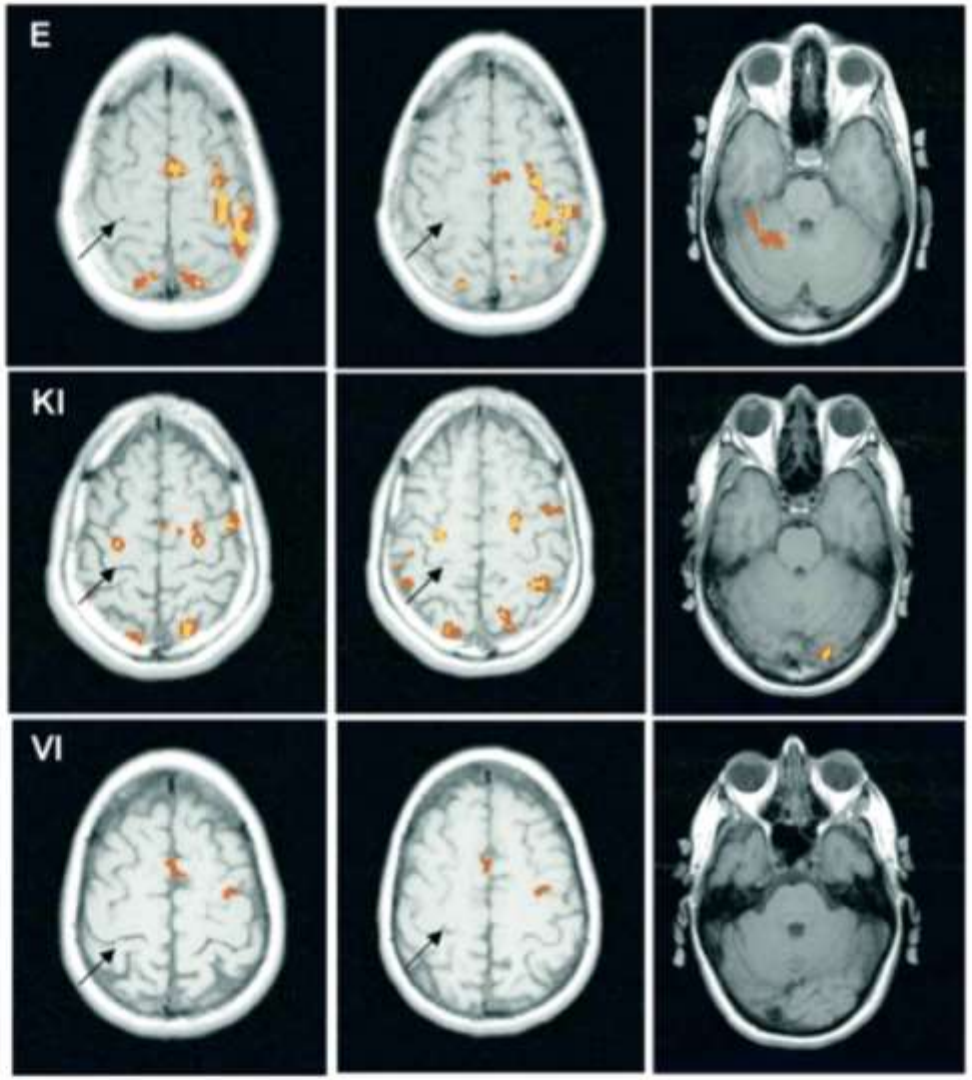
Motor Imagery



VS

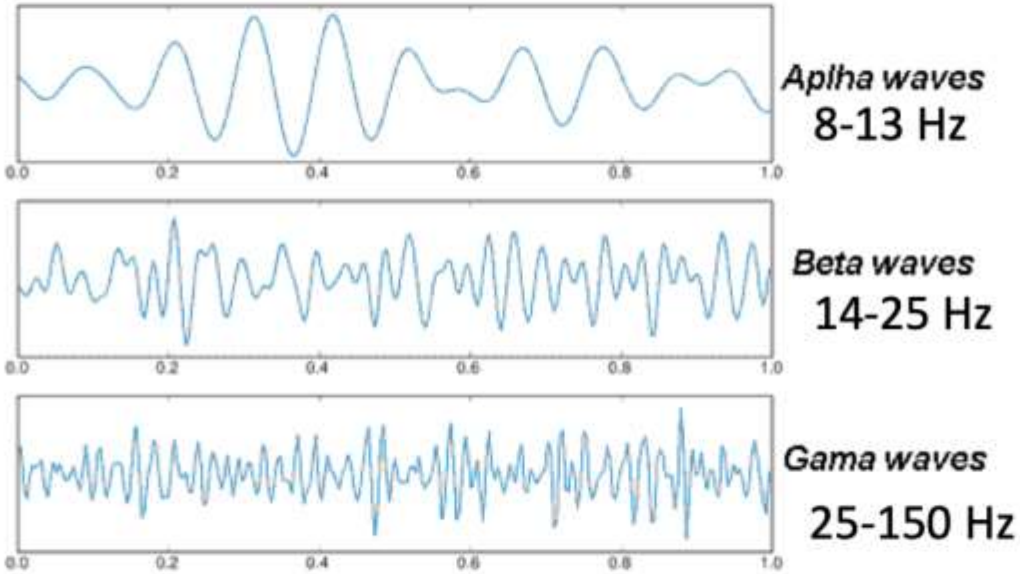


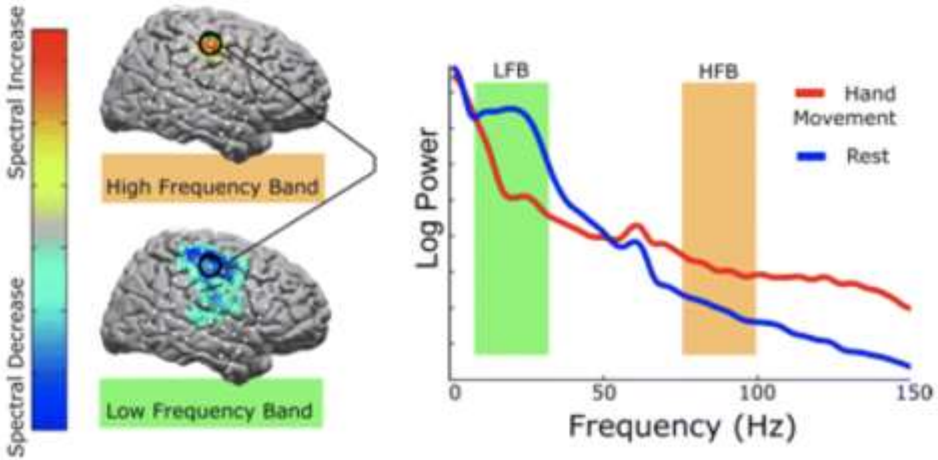
Brain activity during motor action vs imagery

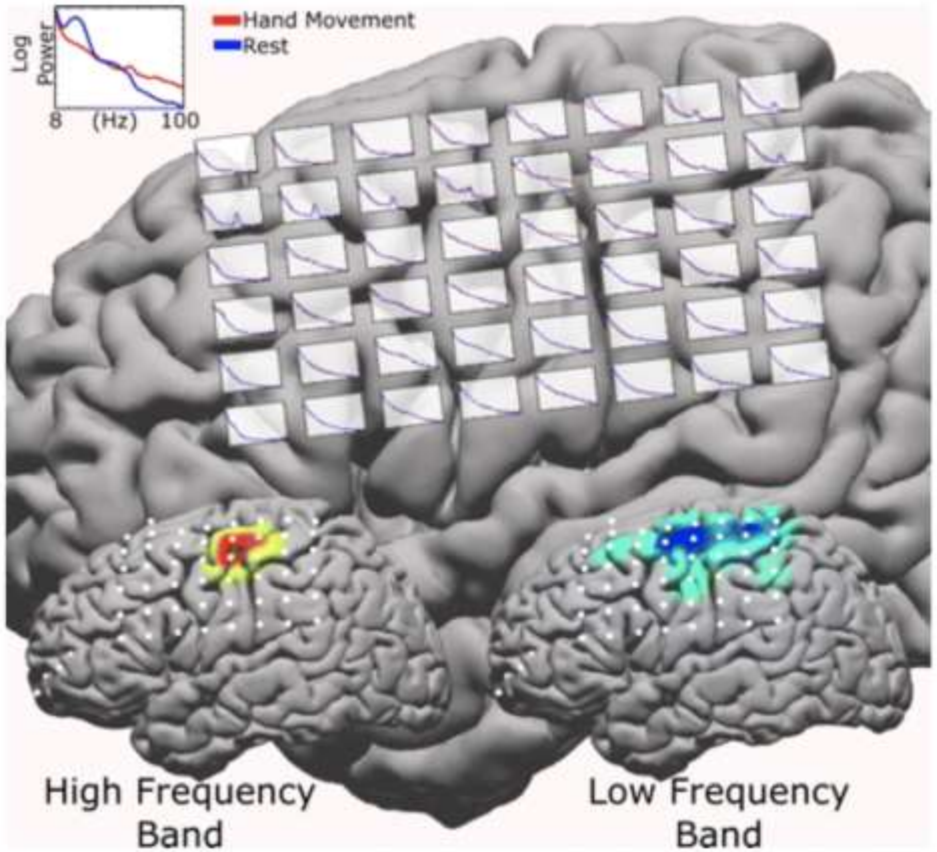


Solodkin et al, 2004

Motor rhythms in cortex







Miller et al, 2007

Goal of the work

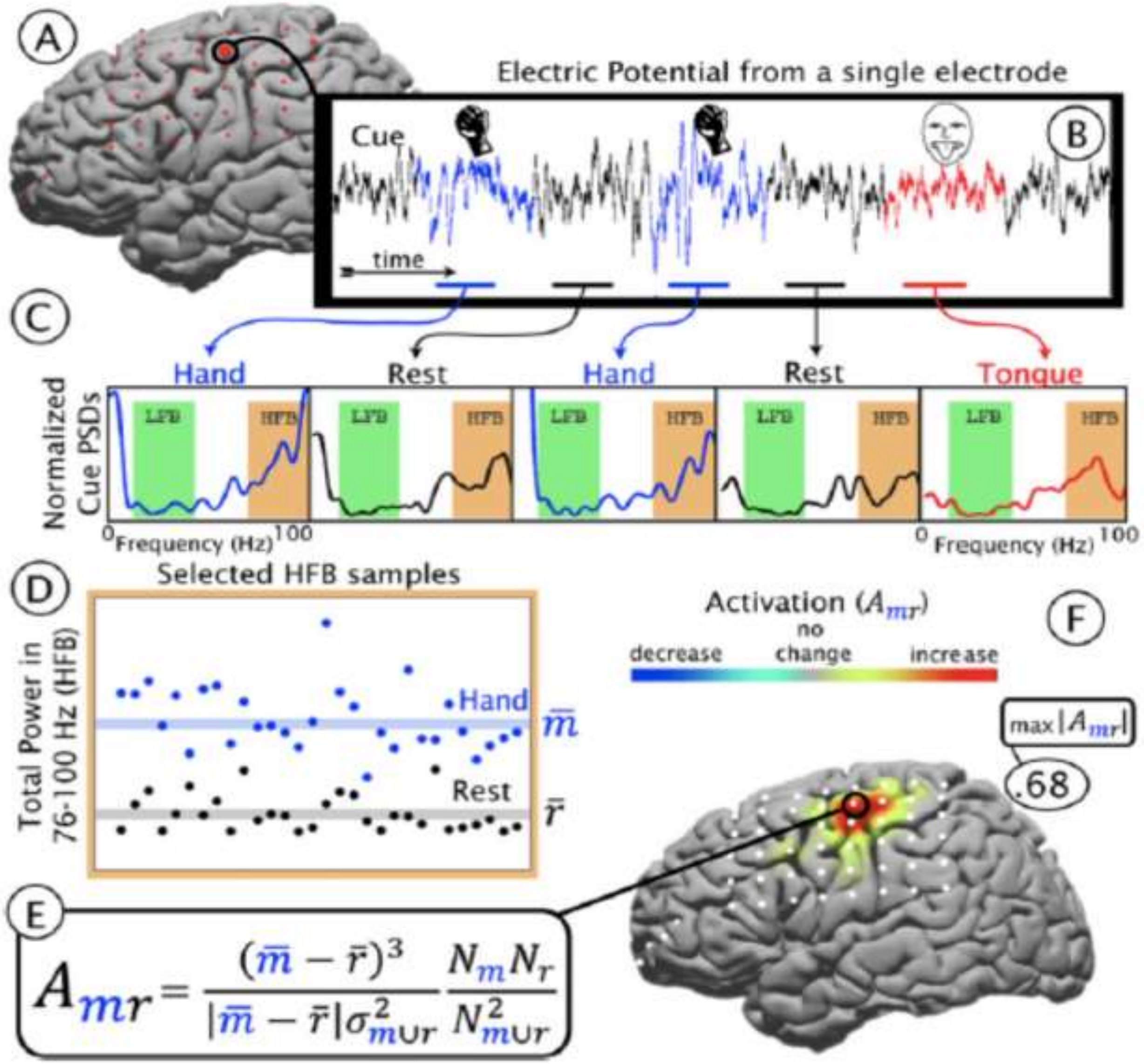
To check whether real movements can be compared with imagery movements.

Methods Used:

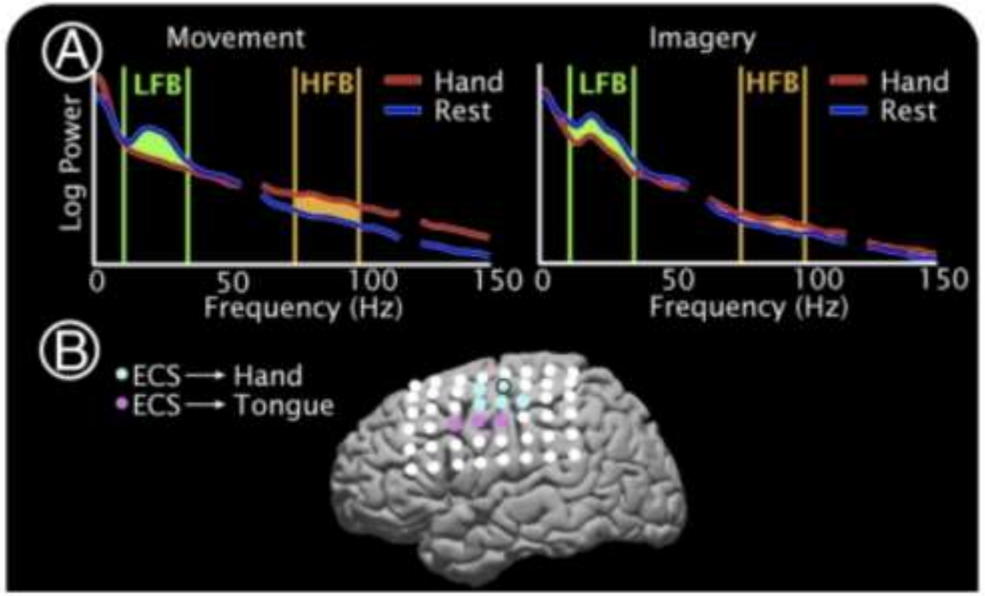
- 8 patients implanted with 4x8 or 8x8 grid

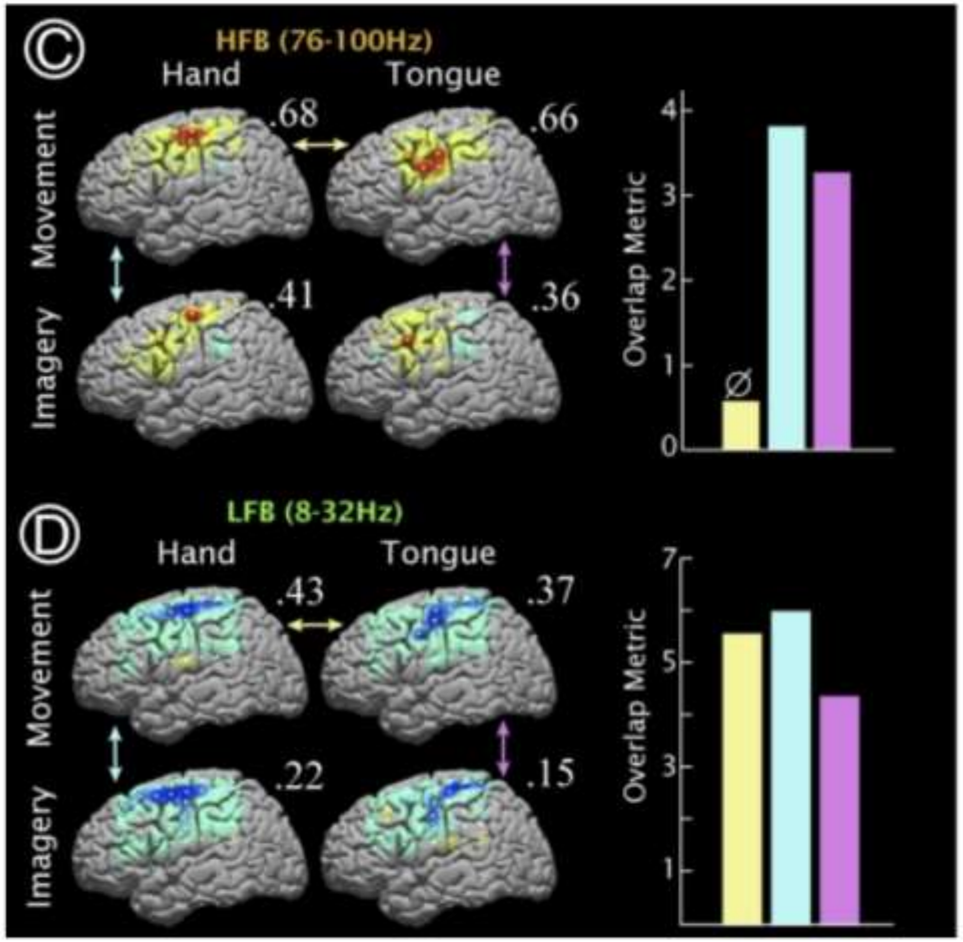
1) Active movements –clench – release of hand, stick out tongue, shoulder shrug, say the word "move"
2) Image movements – same as before

Quantification of brain activity



Cortical activity during real and imagined movements





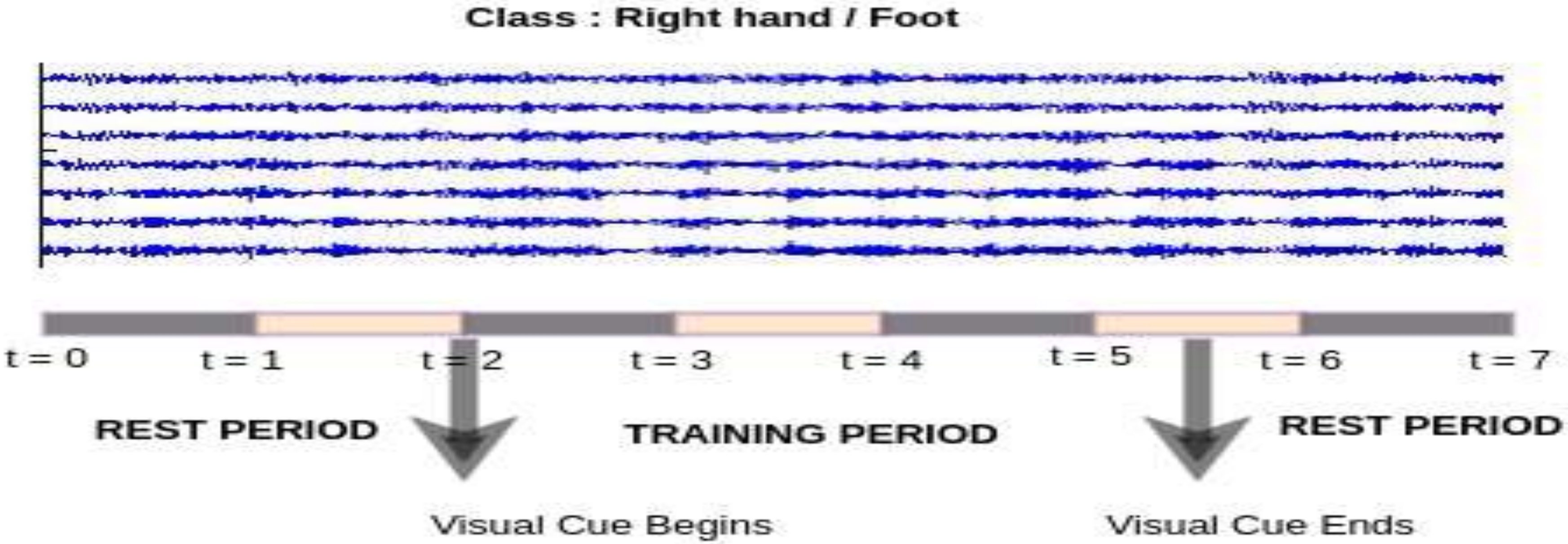
Data Epoching

Selecting data epochs

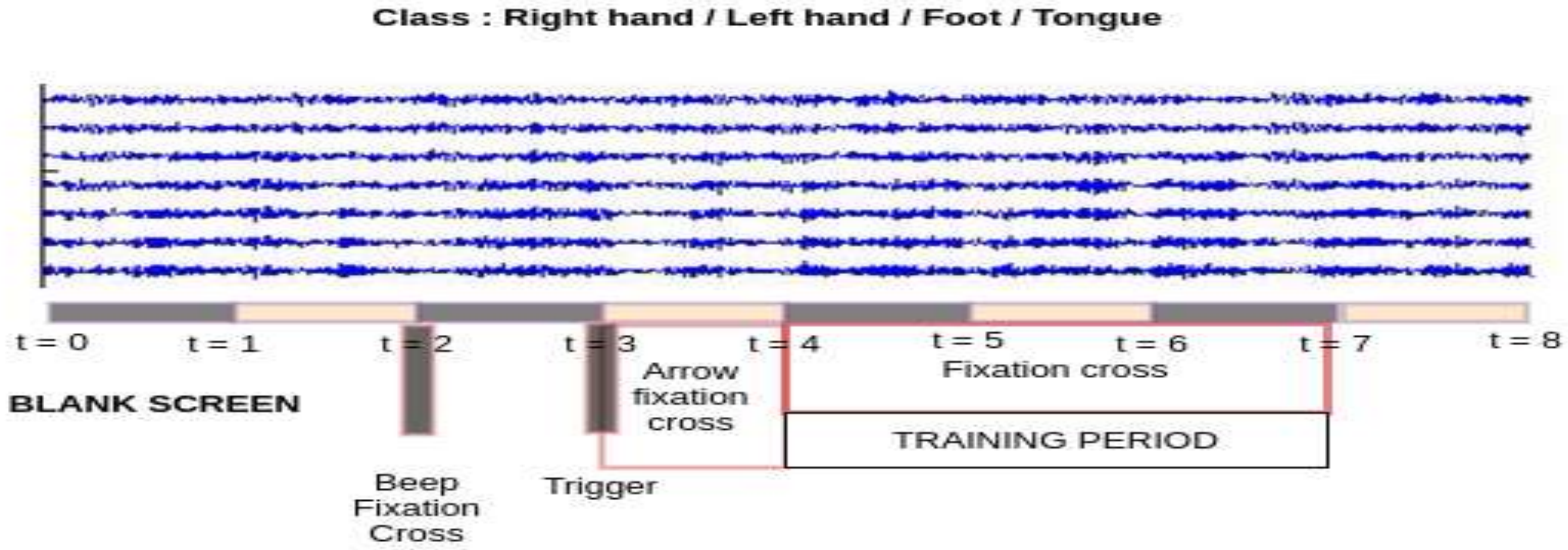
There is no real good reason to select subsets of data epochs. When comparing conditions – performed by creating contrast at the STUDY level (the group analysis interface which may also be used for single-subject analysis) – one may ignore specific data epochs.

- Non-overlapping segments
- Overlapping segments
    - Fully overlapping segments
    - Partially overlapping segments

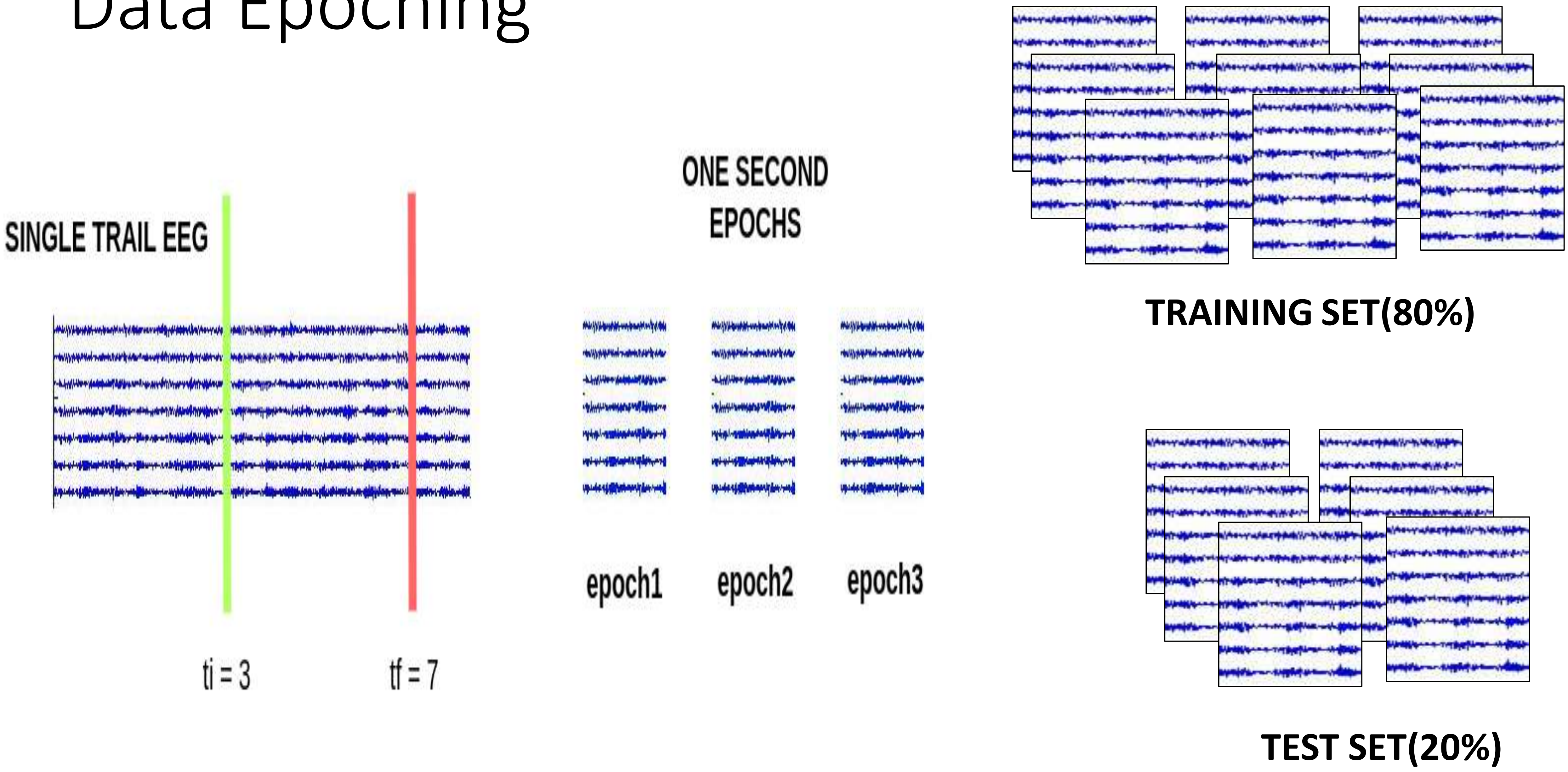
DATASET 1 SINGLE TRIAL



DATASET 2 SINGLE TRIAL



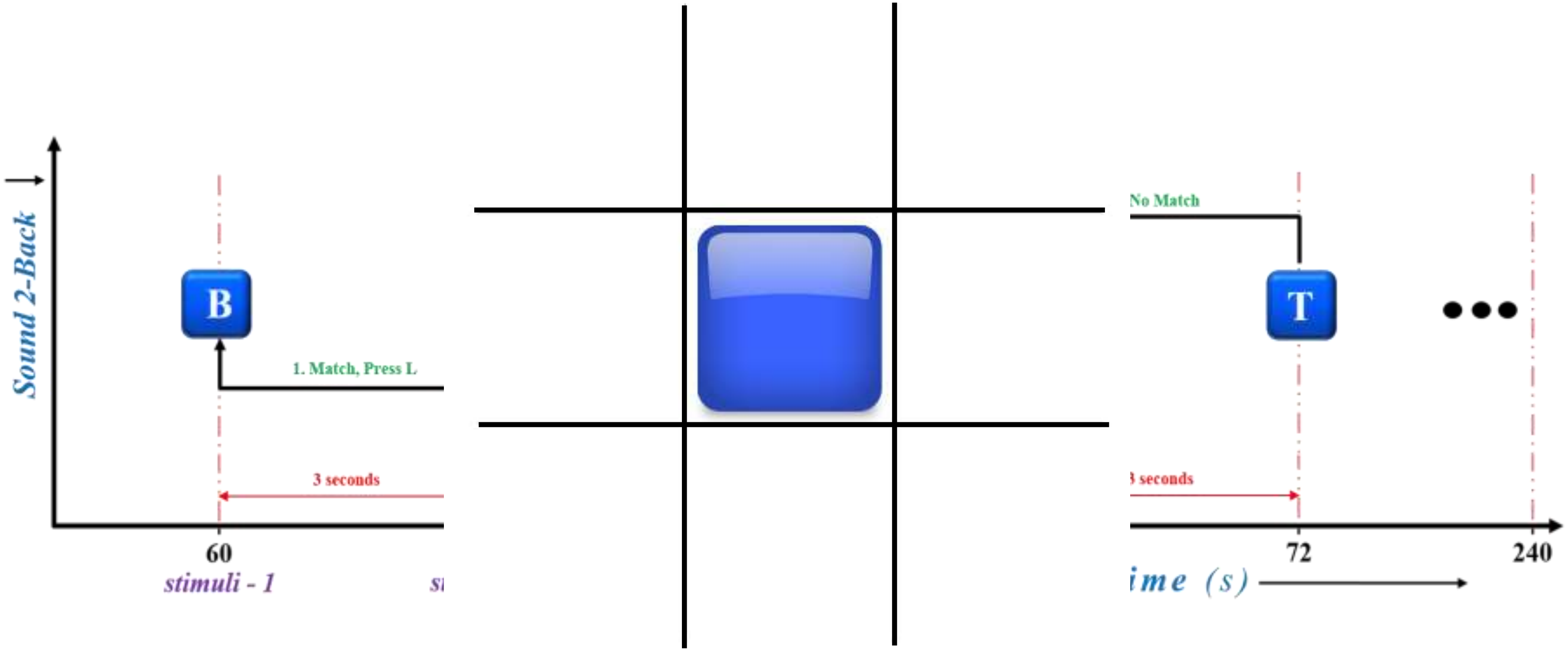
Data Epoching



Cognitive Workload

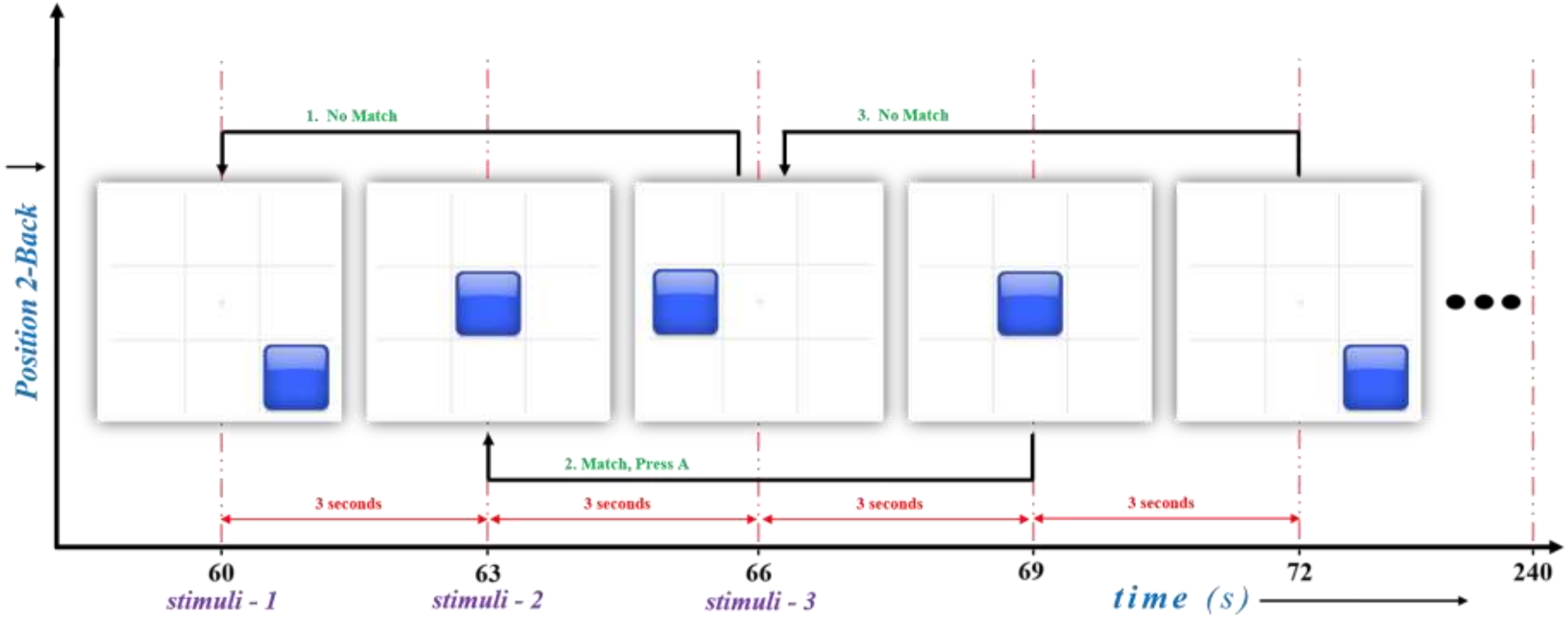
- Cognitive Workload (**CWL)** is a demand placed upon humans for mental recourses while performing a task.
- Mental resources include working memory, ability to process, etc.
- **Working memory (WM)** is a cognitive system with a limited capacity to hold a small amount of information and process it.

n-Back Task



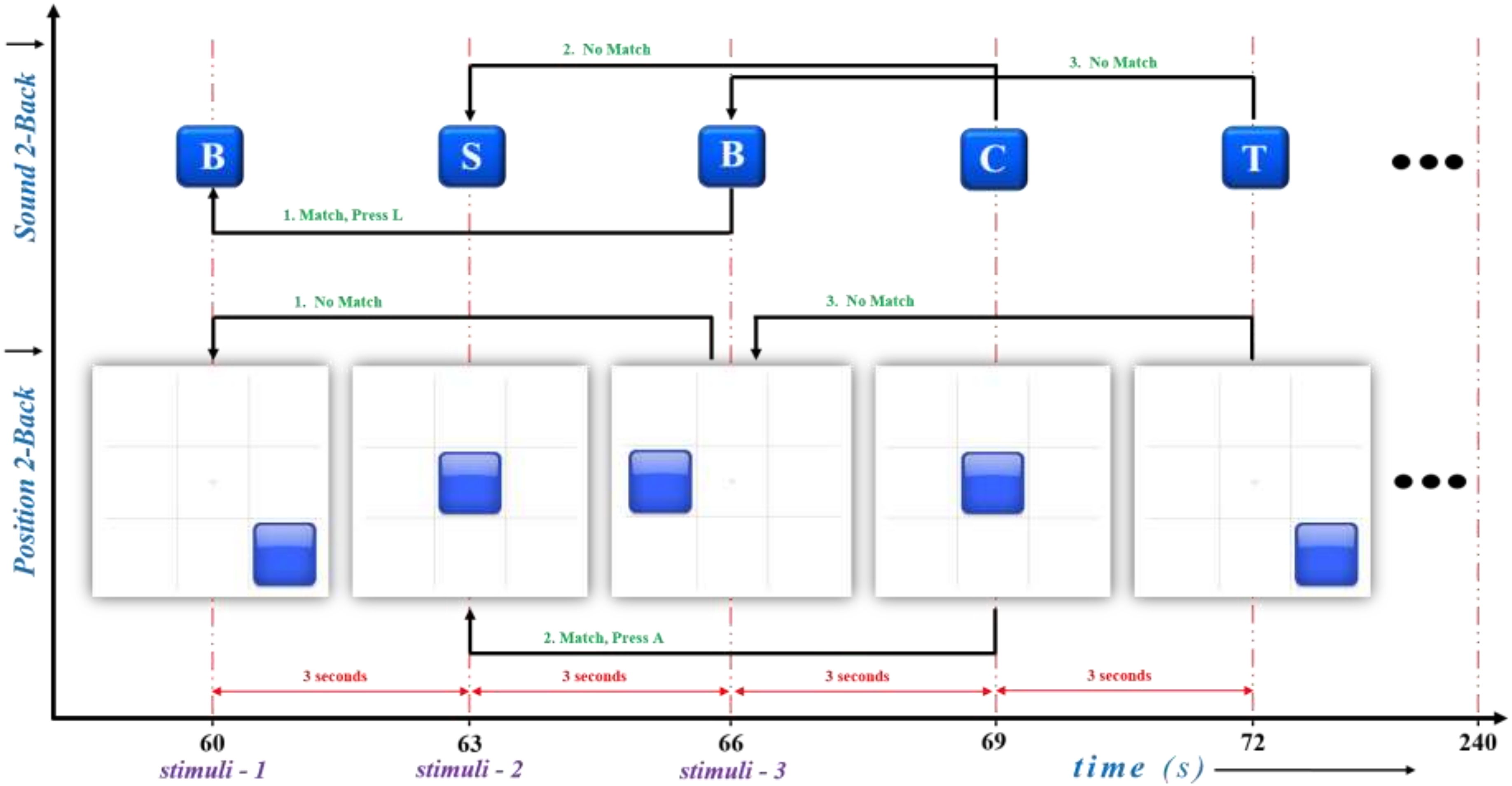
Sound 2-Back

n-Back Task



Position 2-Back

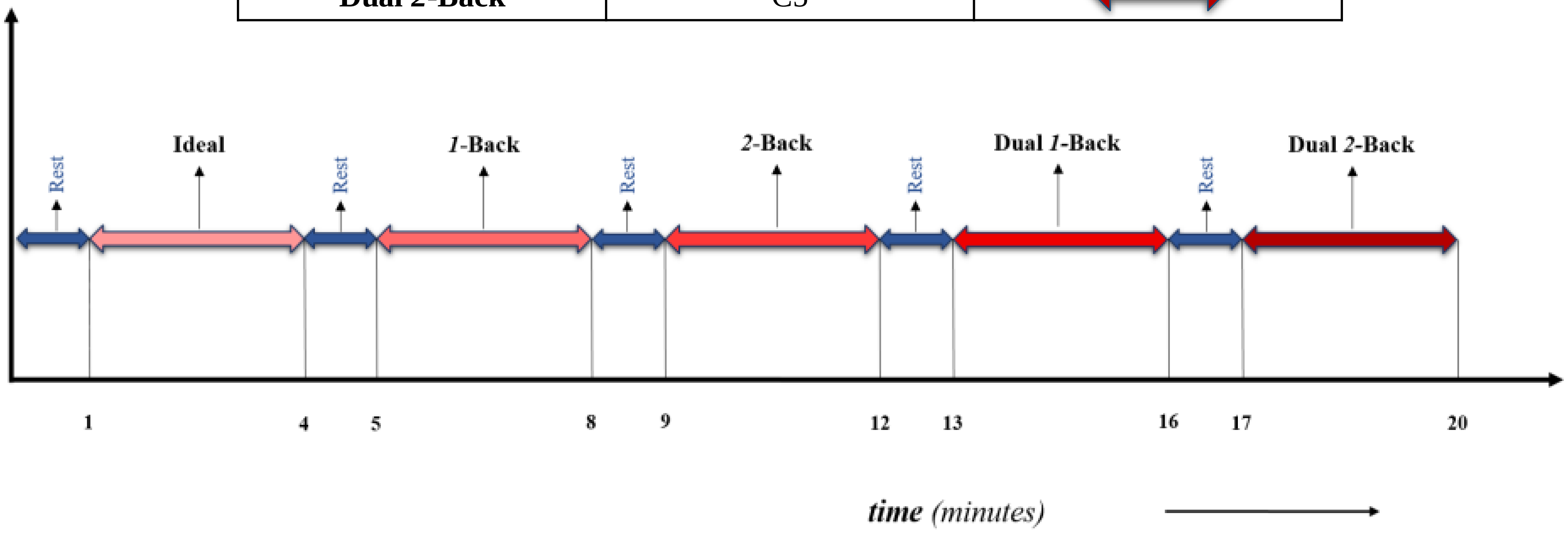
n-Back Task



Sound & Position *2*-Back

Data Epoching

Task	Cognitive Workload Class	Colour Code depicting Load Variation
Idle	C1	
***1*-Back**	C2	
***2*-Back**	C3	
Dual *1*-Back	C4	
Dual *2*-Back	C5	



Thank you!!

Signal Processing

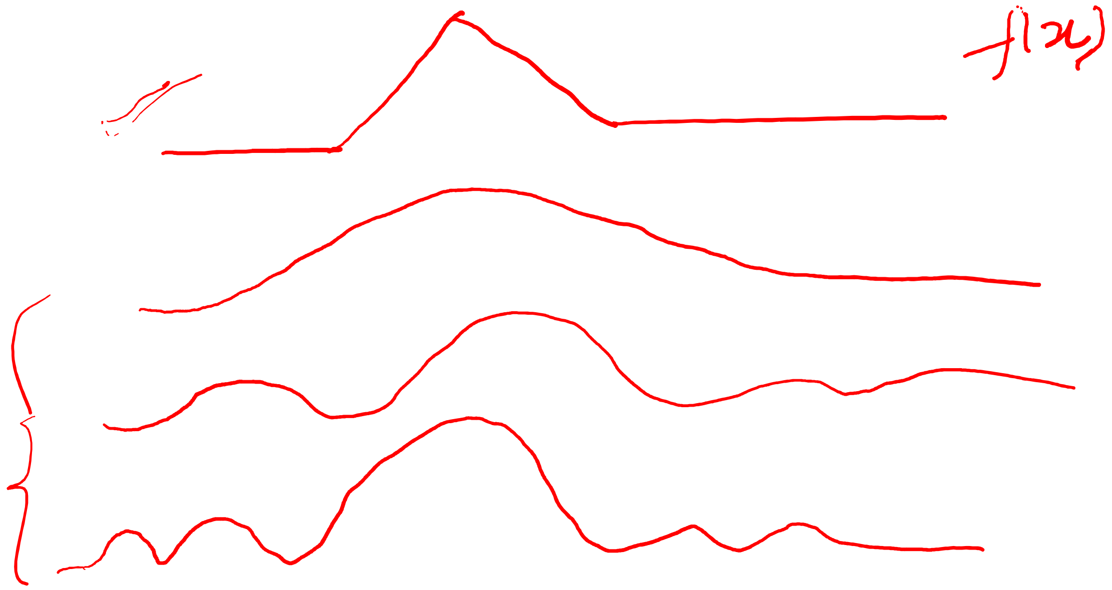
Frequency Domain Analysis

Frequency Domain Analysis

- EEG signals are recorded in the domain of TIME.
- Introduced by J.-B. Joseph Fourier in the early 1800s
- It's a coordinate transform system
- Fourier introduced the concept that sine and cosine functions of increasing frequency provide an orthogonal basis for the space of solution functions.

Fourier Series

- Any arbitrary function can be represented using sine and cosines.
- Sine and cosine form the basis of the function space.

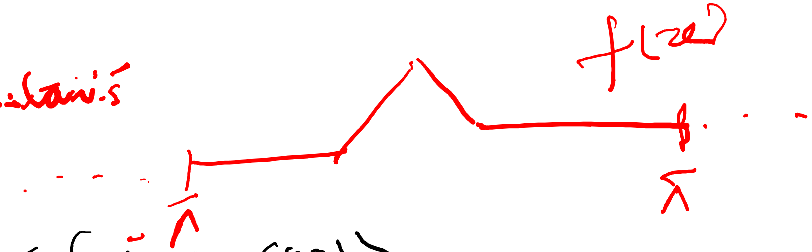


Sum inc. frequencies
sine &
cosine.
approximate

Fourier Series

- Approximating arbitrary function f(x), as a infinite sum of sine and cosine of increasing high frequency.

$$f(x) = \frac{A_0}{2} + \sum_{k=1}^{\infty} \left[A_k \cos(kx) + B_k \sin(kx) \right]$$



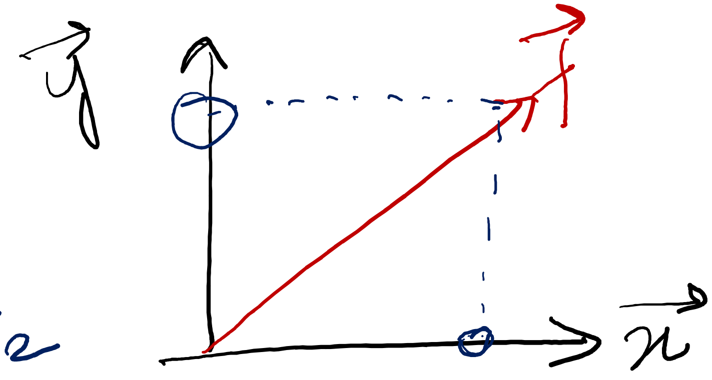
Where A_k & B_k are fourier constants

$$A_k = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x) \cos(kx)\, dx = \frac{1}{\|\cos(kx)\|^2} \langle f(x), \cos(kx) \rangle$$

$$B_k = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x) \cdot \sin(kx)\, dx = \frac{1}{\|\sin(kx)\|^2} \langle f(x), \sin(kx) \rangle$$

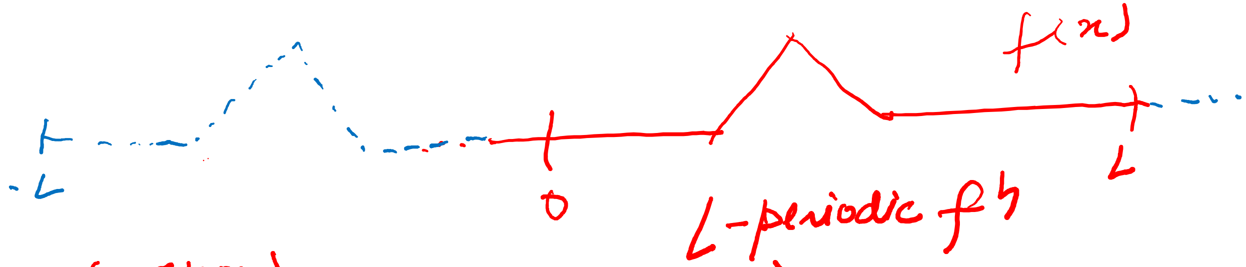
Fourier Series

$$\vec{f} = \langle \vec{f}, \vec{x} \rangle \cdot \frac{\vec{x}}{\|x\|^2} + \langle \vec{f}, \vec{y} \rangle \cdot \frac{\vec{y}}{\|y\|^2}$$



$$f(x) = \frac{f(x) \cdot \cos(kx) \cdot \cos}{\|\cos\|} + \frac{f(x) \cdot \sin(kx) \sin k}{\|\sin\|^2} \to f^n \text{ space}$$

Fourier Series



$$f(x) = \frac{A_0}{2} + \sum_{k=1}^{\infty} \left(A_k \cos\left(\frac{2\pi k x}{L}\right) + B_k \sin\left(\frac{2\pi}{L} k x\right)\right)$$

$$A_k = \frac{2}{L} \int_0^L f(x) \cdot \cos\left(\frac{2\pi}{L} k x\right) dx$$

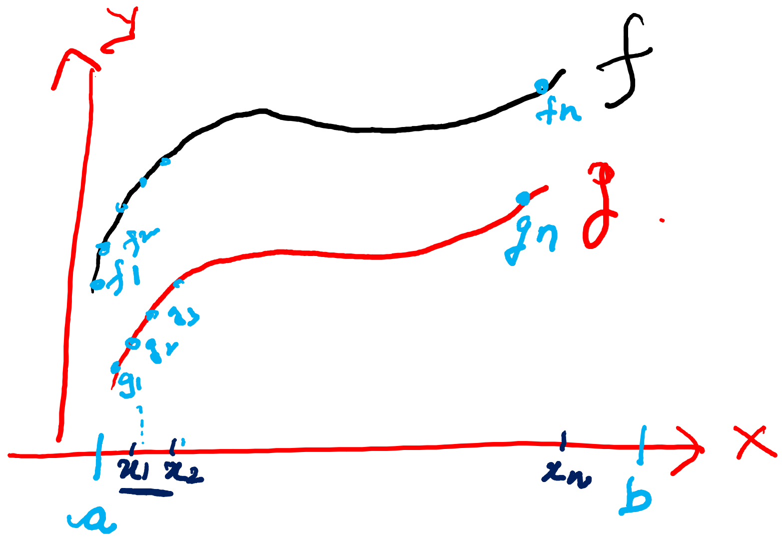
$$B_k = \frac{2}{L} \int_0^L f(x) \cdot \sin\left(\frac{2\pi}{L} k x\right) dx$$

Inner Product of Functions

$f = [f_1 \; f_2 \; \cdots \; f_n]^T$

$g = [g_1 \; g_2 \; \cdots \; g_n]^T$

$$\langle f(x), g(x) \rangle = \int_a^b f(x)\, g(x)\, dx$$



$\Delta x = \dfrac{b-a}{n-1}$

When 'n' data points are increasing

$$\frac{b-a}{n-1} \langle f, g \rangle = \sum_{k=1}^{n} f(x_k)\, g(x_k) \cdot \Delta x$$

$$n \to \infty \equiv \Delta x \to 0$$

Fourier Series for Complex functions

$$f(x) = \sum_{k=-\infty}^{\infty} C_k e^{ikx}$$

$$\left[e^{ikx} = \cos(kx) + i \sin(kx) \right\}$$

Euler expansion

$i = \sqrt{-1}$

$$f(x) = \sum_{k=-\infty}^{\infty} \underline{(\alpha_k + i\beta_k)} \left[\cos(kx) + i \sin(kx)\right]$$

$$= (\alpha_0 + i\beta_0) + \sum_{k=1}^{\infty} \left[(\underline{\alpha_{-k}} + \underline{\alpha_k}) \cos(kx) + (\underline{\beta_{-k}} - \underline{\beta_k}) \sin(kx) \right]$$

$$+ i \sum_{k=1}^{\infty} \left[(\beta_{-k} + \beta_k) \cos(kx) - (\alpha_{-k} - \alpha_k) \sin(kx) \right]$$

Let $e^{ikx} = \cos(kx) + \sin(kx) = \psi_k \qquad k \in \mathbb{Z}$

$$\underline{\underline{\langle \psi_j, \psi_k \rangle}} = \int_{-\pi}^{\pi} e^{ijx} e^{-ikx}\,dx = \int_{-\pi}^{\pi} e^{i(j-k)x}\,dx$$

$$= \frac{1}{i(j-k)}\left[e^{i(j-k)x}\right]_{-\pi}^{\pi} = \begin{cases} 0, & \text{if } j \neq k \\ 2\pi, & \text{if } j = k \end{cases}$$

we can write as

$$\boxed{\underline{\underline{\frac{1}{2\pi}}} \sum_{k=-\infty}^{\infty} \underbrace{\langle f(x), \psi_k \rangle}_{c_k} \underbrace{\psi_k}_{e^{ikx}}}$$

$\|\psi_k\|^2 = 2\pi$

③ Fourier Transform is a linear operator

$$\mathcal{F}(\alpha f(x) + \beta g(x)) = \alpha \mathcal{F}(f(x)) + \beta \mathcal{F}(g(x))$$

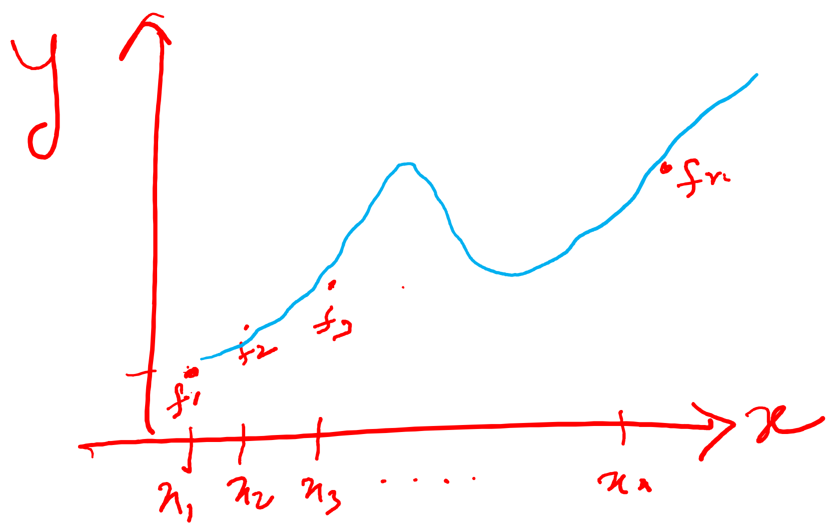
$$\mathcal{F}^{-1}(\alpha \hat{f}(\omega) + \beta \hat{g}(\omega)) = \alpha \mathcal{F}^{-1}(\hat{f}(\omega)) + \beta \mathcal{F}^{-1}(\hat{g}(\omega))$$

④ Parseval's theorem

$$\underbrace{\int_{-\infty}^{\infty} |\hat{f}(\omega)|^2 \, d\omega}_{} = \underbrace{2\pi \int_{-\infty}^{\infty} |f(x)|^2 \, dx}_{}$$

Discrete Fourier Transform

$$\begin{bmatrix} f_0 \\ f_1 \\ f_2 \\ \vdots \\ f_n \end{bmatrix} \begin{bmatrix} & & \\ & & \\ & & \end{bmatrix} = \begin{bmatrix} \hat{f}_0 \\ \hat{f}_1 \\ \hat{f}_2 \\ \vdots \\ \hat{f}_n \end{bmatrix}$$



$$\hat{f}_k = \sum_{j=0}^{n-1} f_j \, e^{-i2\pi jk/n}$$

$$f_k = \left[\sum_{j=0}^{n-1} \hat{f}_j \, e^{i2\pi jk/n}\right] \cdot \frac{1}{n}$$

$$\{f_0, f_1, f_2 \dots f_n\} \xRightarrow{DFT} \{\hat{f}_0, \hat{f}_1, \dots \hat{f}_n\}$$

$\hat{f}$:- how much of each freq. is required to reconstruct the data in f.

$$f_j \, \underbrace{e^{-i2\pi jk/n}} \Rightarrow \underline{e^{-2\pi i/n}} \Rightarrow \text{"}\underline{\omega_n}\text{"} \rightarrow \text{fundamental freq.}$$

[approximation in form of sine & cosines with n discrete values]

$$\hat{f}_k = \sum_{j=0}^{n-1} f_j \, e^{-i2\pi jk/n}$$

$$\begin{bmatrix} \hat{f}_0 \\ \hat{f}_1 \\ \vdots \\ \hat{f}_n \end{bmatrix} = \begin{array}{c} \\ k \rightarrow \end{array} \underbrace{\begin{bmatrix} 1 & 1 & 1 & \cdots & 1 \\ 1 & \omega_n & \omega_n^2 & \cdots & \omega_n^{n-1} \\ 1 & \omega_n^2 & \omega_n^4 & \cdots & \omega_n^{2(n-1)} \\ \vdots & & & & \\ 1 & \omega_n^{n-1} & \omega_n^{2(n-1)} & \cdots & \omega_n^{(n-1)^2} \end{bmatrix} \begin{bmatrix} f_0 \\ f_1 \\ \vdots \\ f_n \end{bmatrix}}$$

DFT → Mathematical Transform

FFT → computationally efficient way of computing DFT

FAST FOURIER TRANSFORM

$$\text{DFT} = [\ ]_n [\ ]_n \rightarrow \underline{O(n^2)}$$

$$\text{FFT} \longrightarrow O(n \log n)$$

$$\left[\quad\right]_{n^2} \longrightarrow n \log n$$

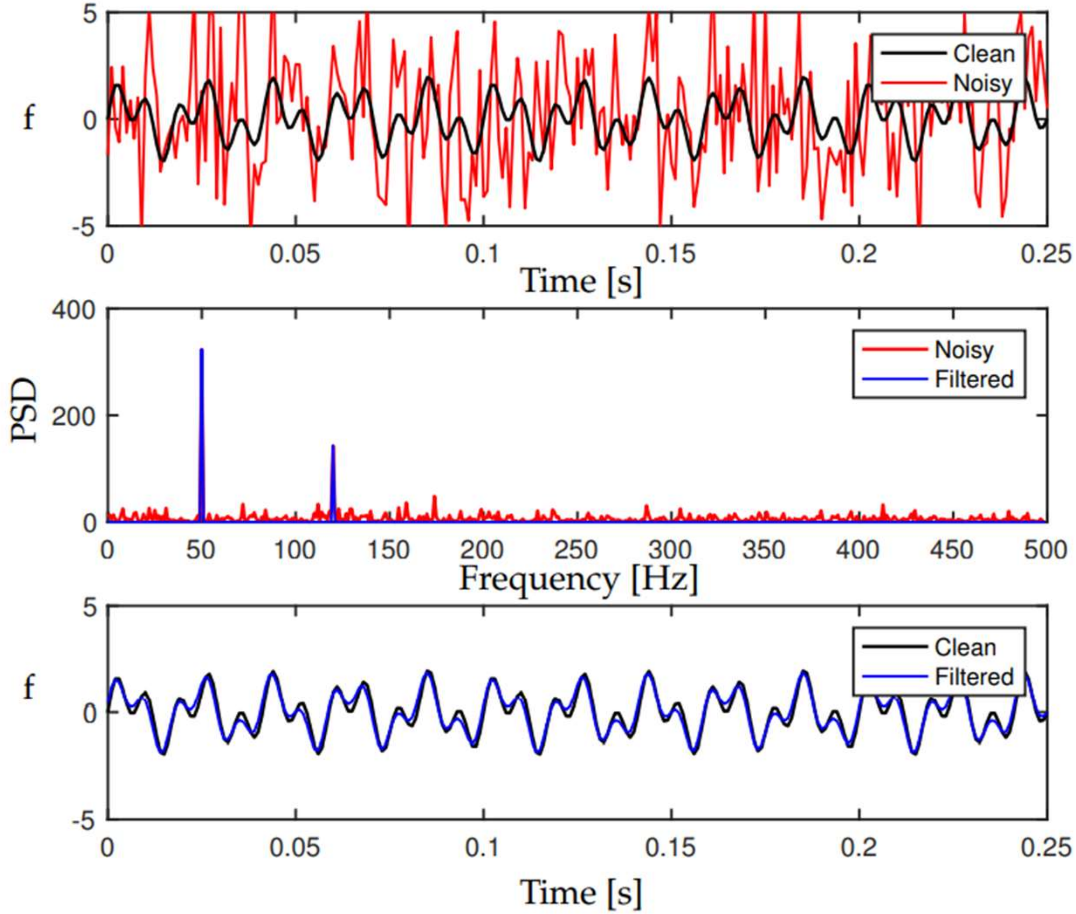
Ex $\quad \hat{f} = \underline{F_{1024}}\, f \qquad \{ n = 1024 \text{ or } \underline{2^{10}} \}$

$$= \underline{\begin{bmatrix} I_{512} & -D_{512} \\ I_{512} & -D_{512} \end{bmatrix} \begin{bmatrix} F_{512} & 0 \\ 0 & F_{512} \end{bmatrix} \begin{bmatrix} f_{even} \\ f_{odds} \end{bmatrix}} \qquad \left\{ \begin{matrix} f_1 \\ f_2 \\ f_3 \\ \vdots \\ f_n \end{matrix} \right\}$$

$$\underline{D_{512}} = \begin{bmatrix} 1 & 0 & & 0 \\ & \omega & & \\ 0 & & \omega^2 & 0 \\ & & \ddots & \\ 0 & & 0 & \omega^{512} \end{bmatrix}$$

$$\left\{ \underrightarrow{F_{1024} \to F_{512} \to F_{256} \to F_{128}} \to \cdots \to \underline{F_2} \right\}$$

$$\begin{bmatrix} - & - \\ - & - \end{bmatrix}_{2\times 2}$$


Clean
Noisy
f
Time [s]
Noisy
Filtered
PSD
Frequency [Hz]
Clean
Filtered
f
Time [s]

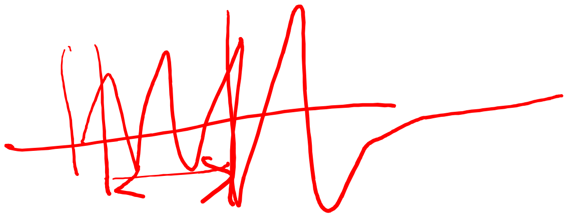
Wavelet Transform

FFT → basis f^n → cosine & sine

Signals which are non periodic, finite, discontinuous

EEG → non-stationary

(1) → Perform fourier analysis over short time windows known as Short time fourier transform (STFTs)



STFT

Wavelet transform

finite Basis function → wavelets → scaled over a

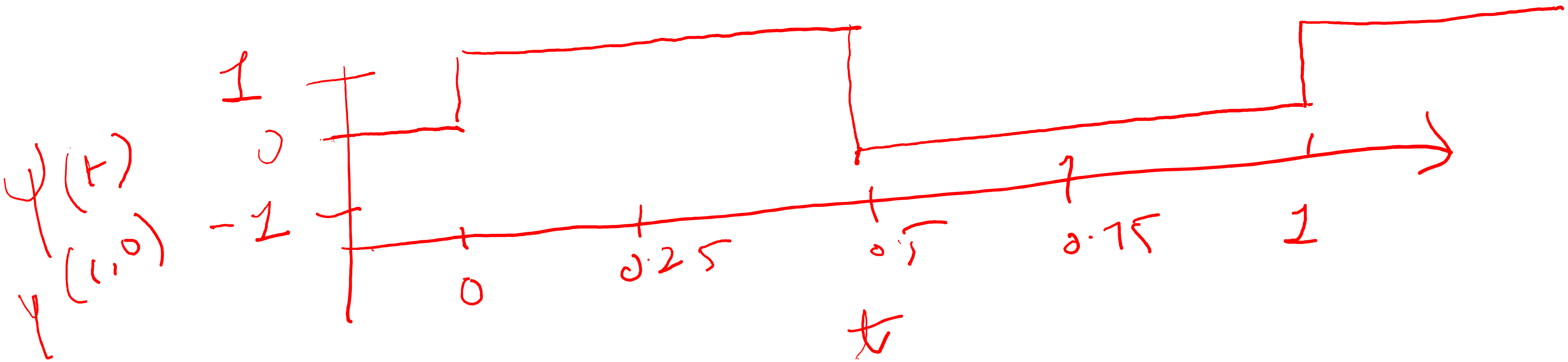
single finite length waveform → Mother Wavelets

$\psi(t) \rightarrow$ mother wavelet

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}}\,\psi\left(\frac{t-b}{a}\right)$$

Haar Wavelet

$$\psi(t) = \begin{cases} 1 & 0 \le t < 1/2 \\ -1 & -1/2 \le t \le 1 \\ 0 & \text{otherwise} \end{cases}$$



continuous WT

$$W_\psi(f)(a,b) = \langle f, \psi_{a,b} \rangle = \int_{-\infty}^{\infty} f(t)\, \psi_{a,b}(t)\, dt$$

Inverse CWT

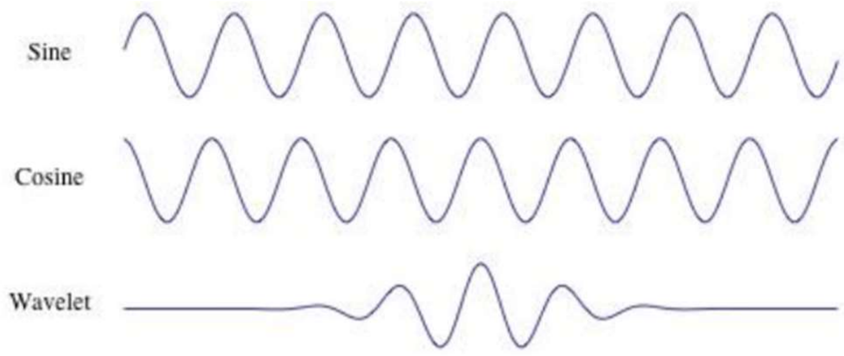
$$f(t) = \frac{1}{C_\psi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} W_\psi(f)(a,b)\, \psi_{a,b}(t)\, \frac{1}{a^2}\, da\, db$$

$$C_\psi = \int_{-\infty}^{\infty} \frac{|\psi(\omega)|^2}{|\omega|}\, d\omega$$

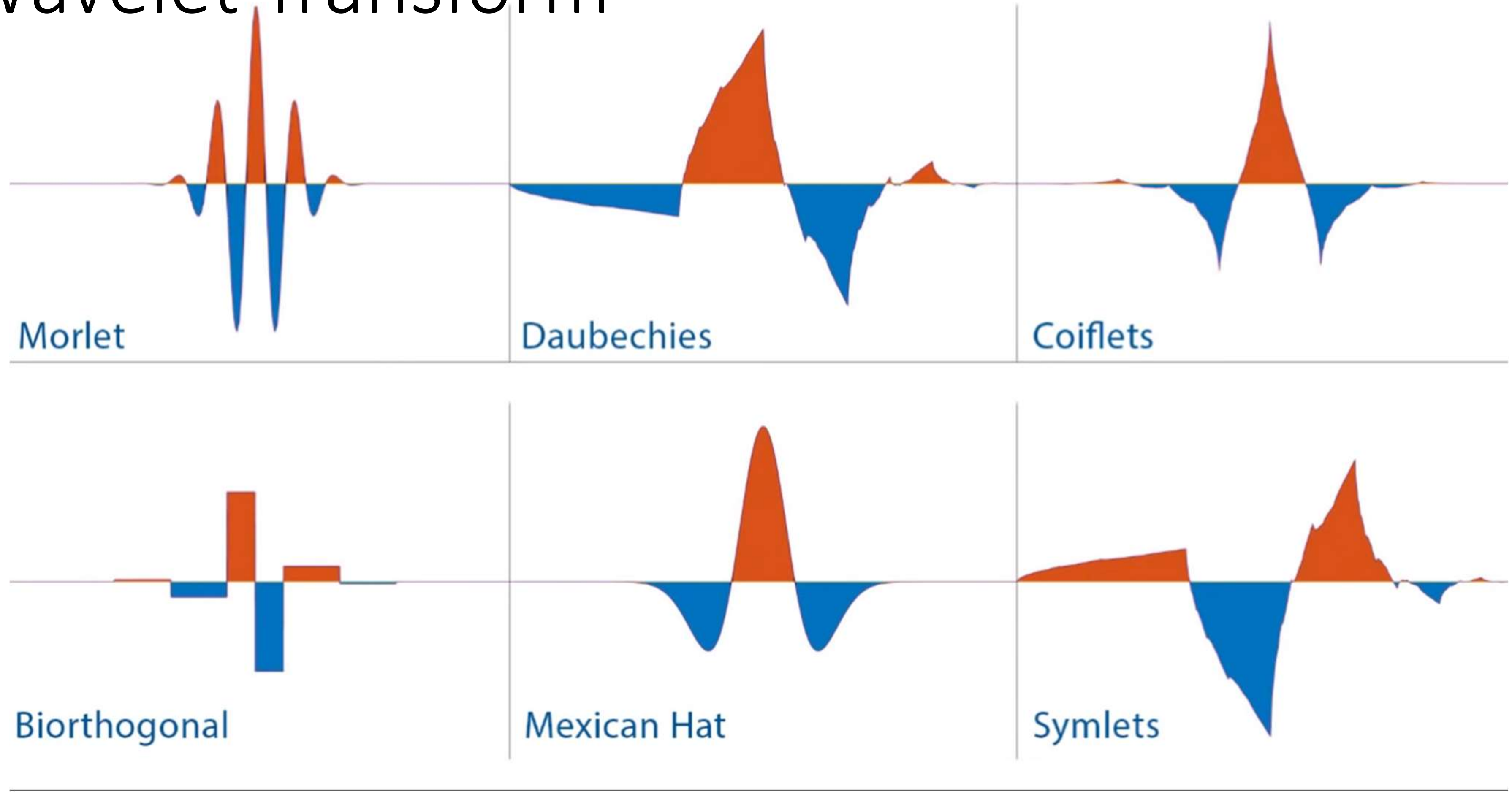
DWT

$$D_{\psi}(f)(j,k) = \langle f, \psi_{j,k} \rangle = \int_{-\infty}^{\infty} f(t)\,\psi_{j,k}(t)\,dt$$

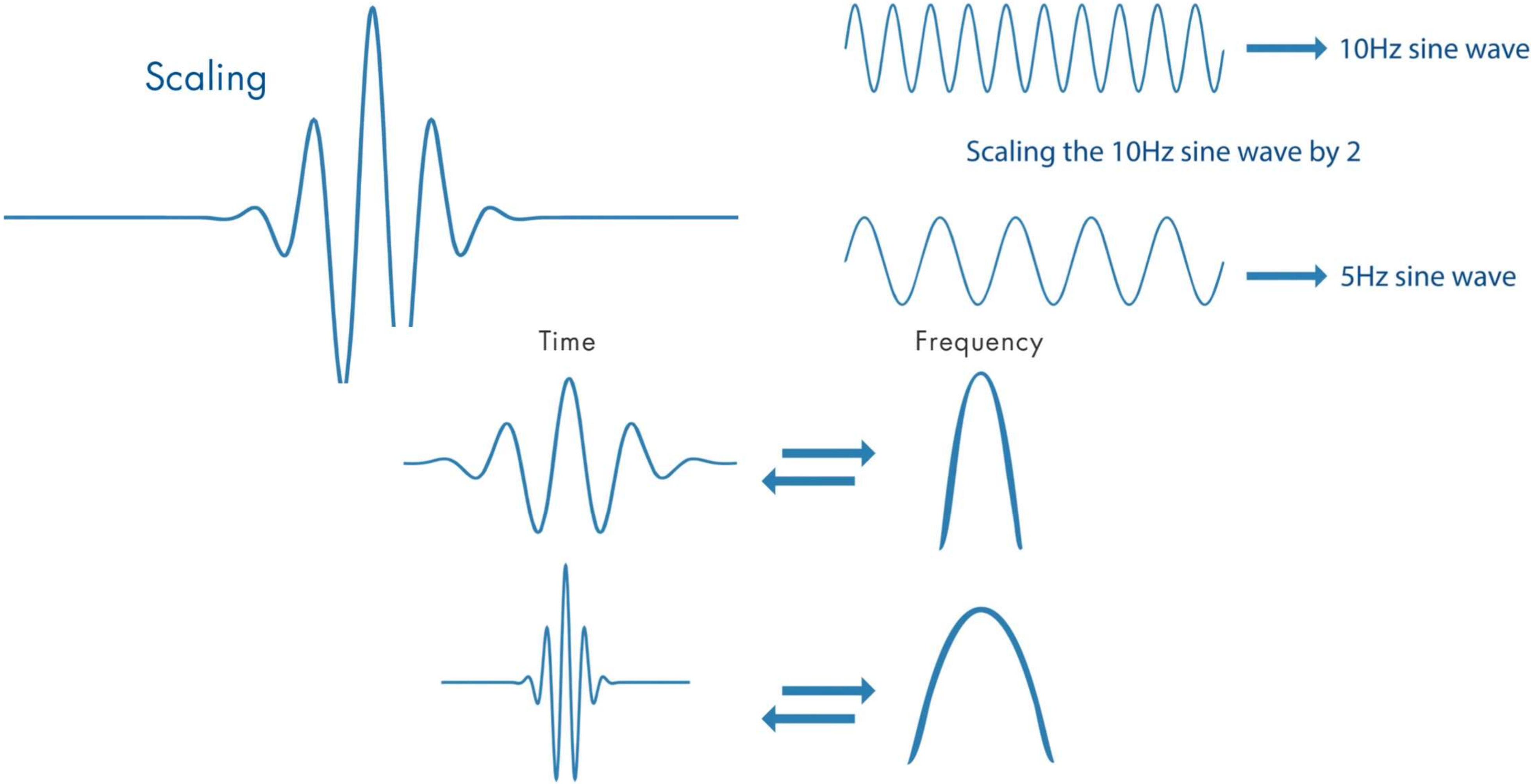
$$\psi_{j,k}(t) = \frac{1}{a^{j}}\,\psi\left(\frac{\theta - kb}{a^{j}}\right)$$


Sine
Cosine
Wavelet

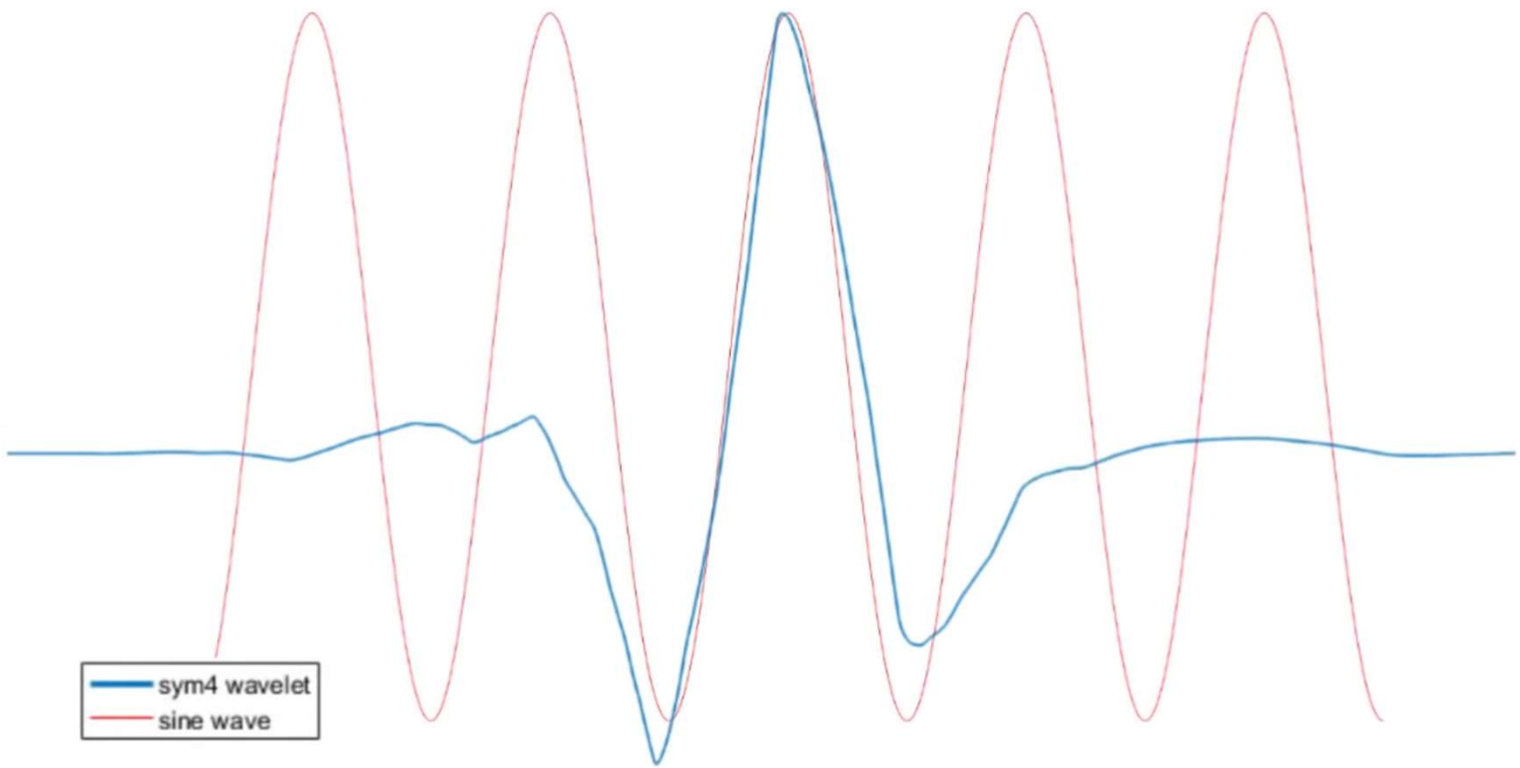
Wavelet Transform



Wavelet Transform



Wavelet Transform



Comparison of a Wavelet with a Sine Wave of Same Frequency

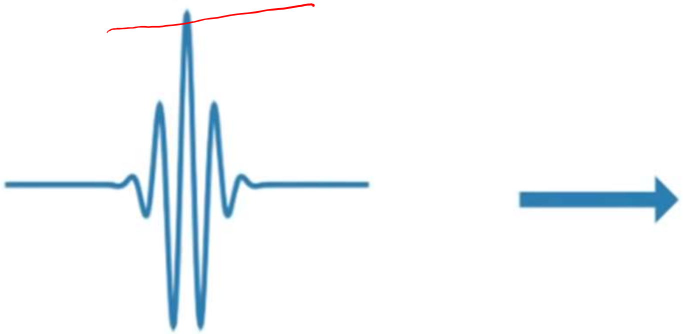
Wavelet Transform

$$\Psi\left(\frac{t}{s}\right)$$

$\psi(t) = \frac{1}{\sqrt{a}}$

large scale factor
low frequency

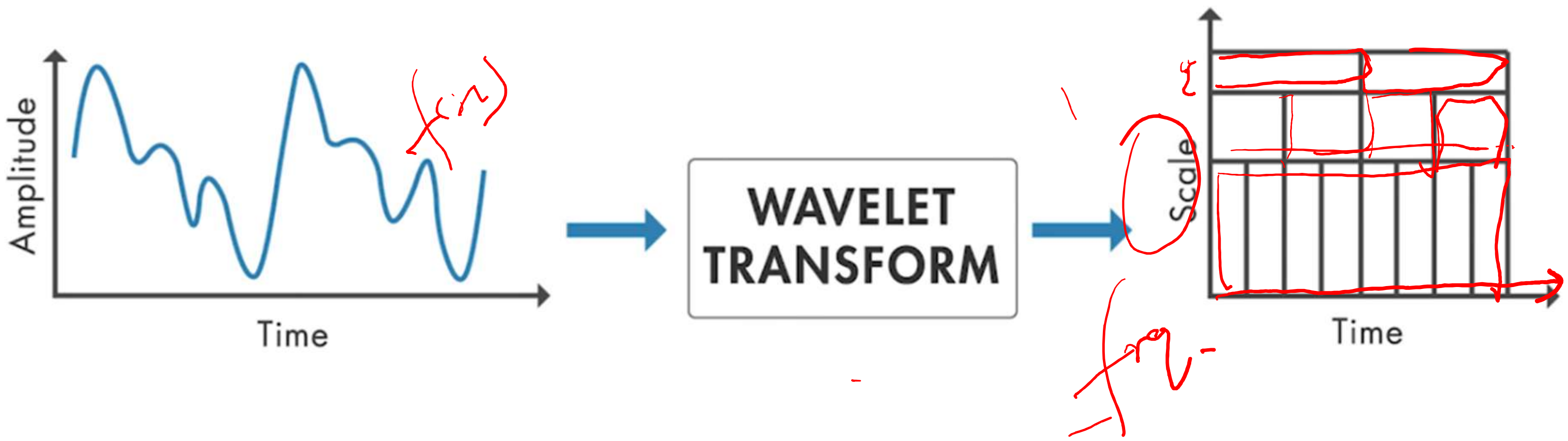
$s > 1$



small scale factor
high frequency

$0 < s < 1$

Continuous Wavelet Transform



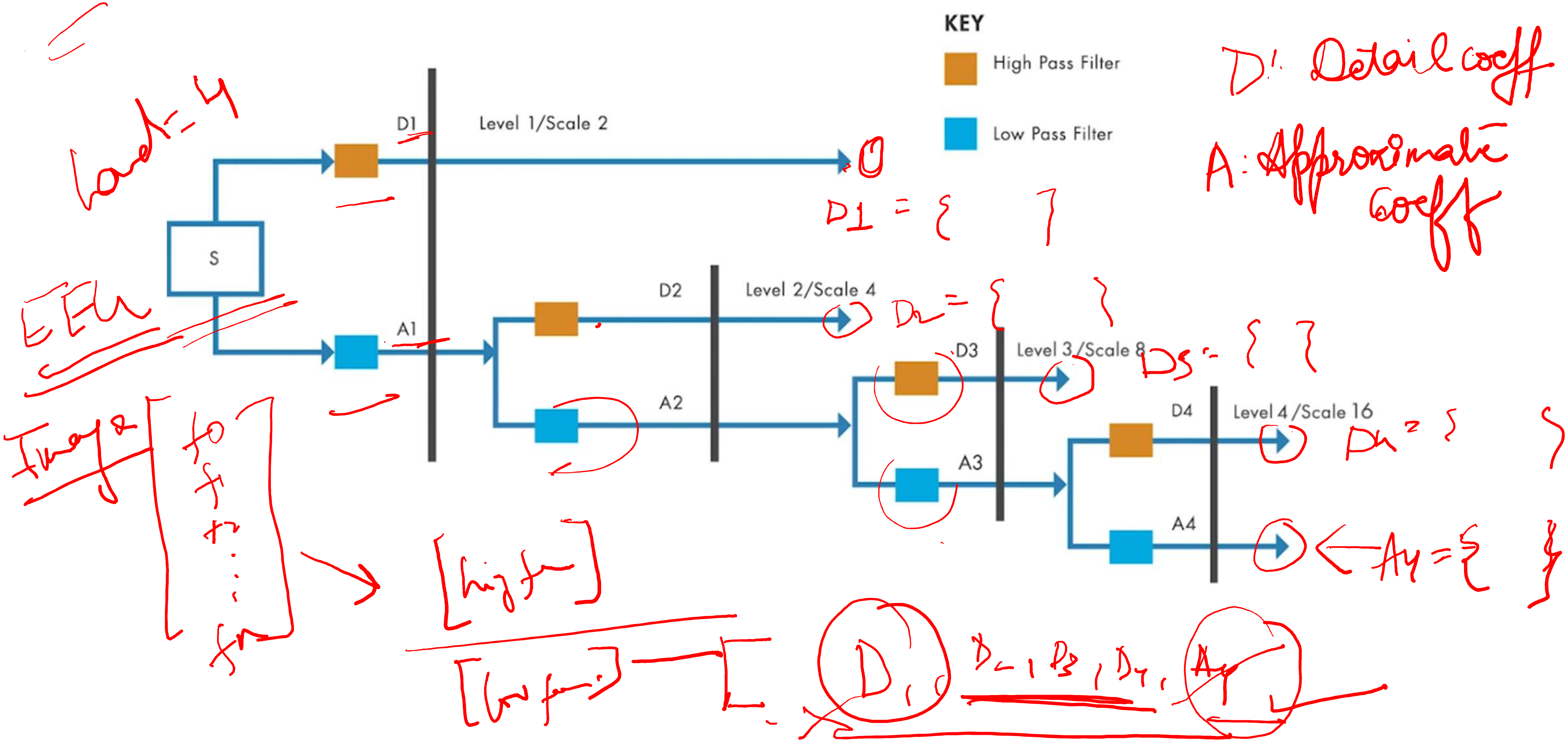
Discrete Wavelet Transform

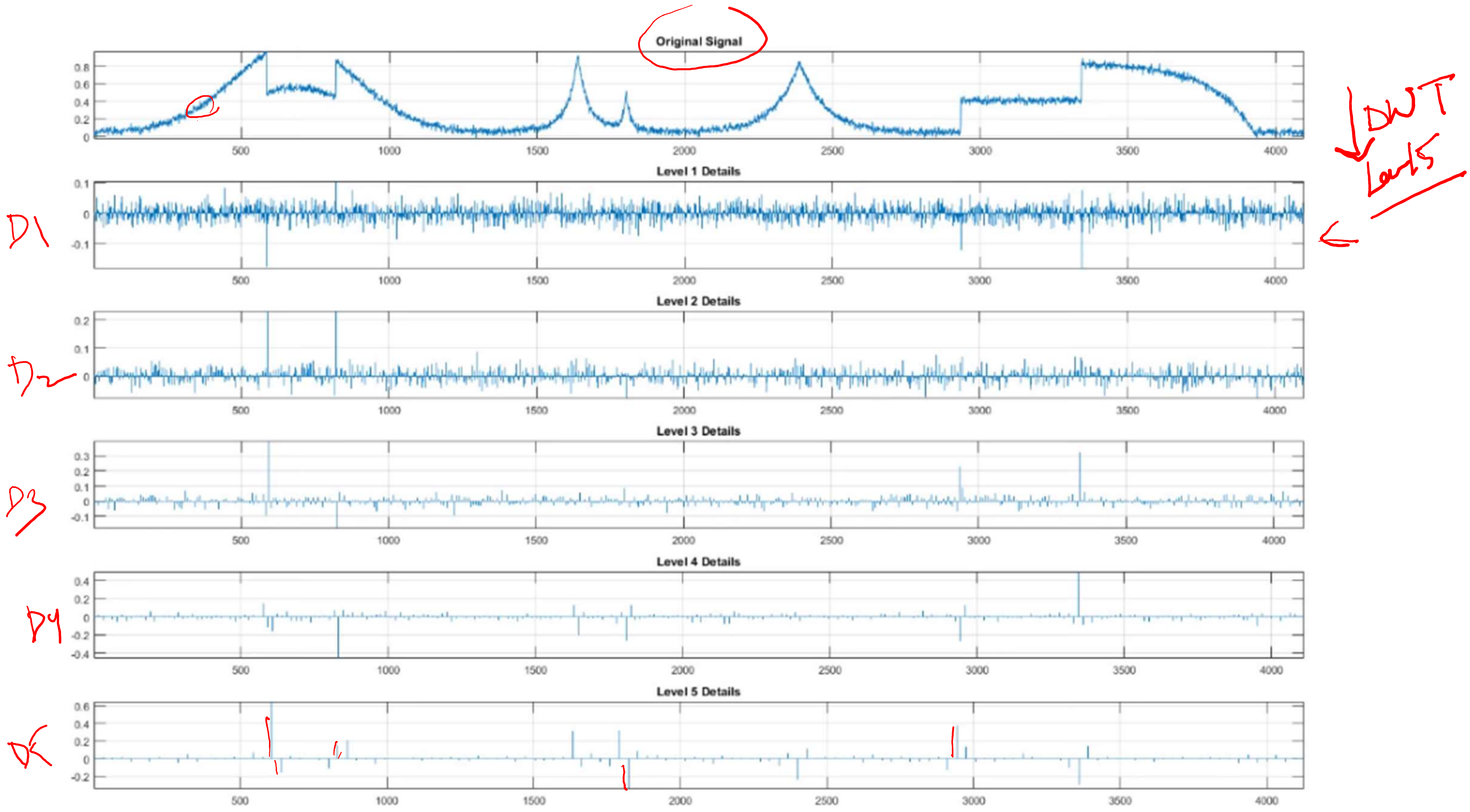
← EEG

FFT | DWT

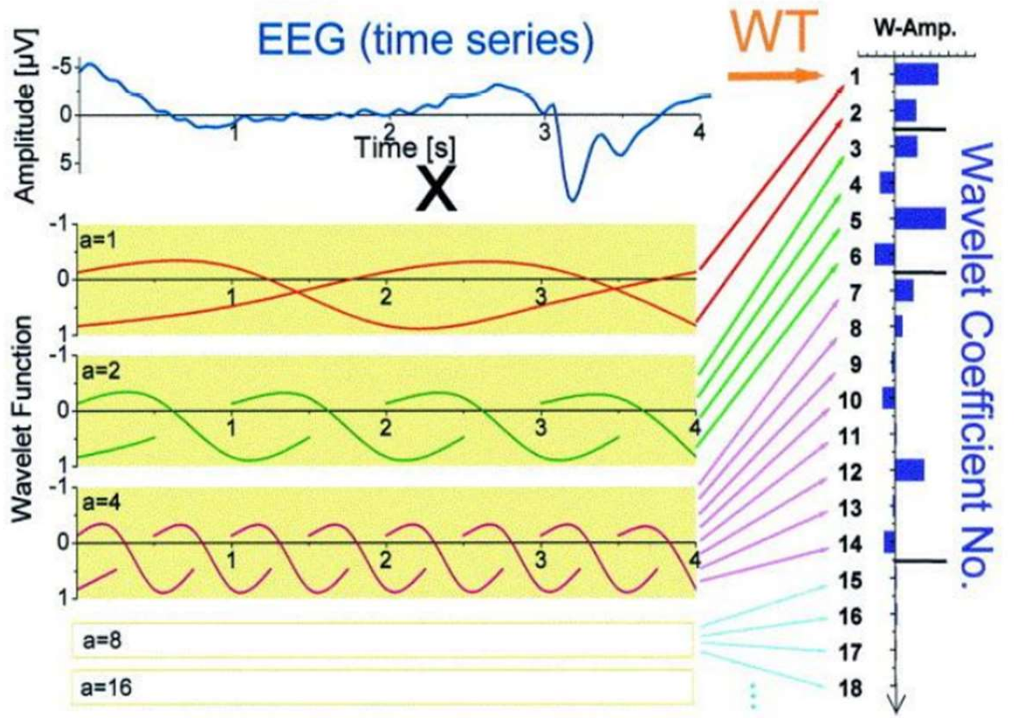
D: Detail coeff

A: Approximate coeff




Original Signal
Level 1 Details
Level 2 Details
Level 3 Details
Level 4 Details
Level 5 Details
D1
D2
D3
D4
D5
DWT
Levels

Example: Wavelet Decomposition of EEG



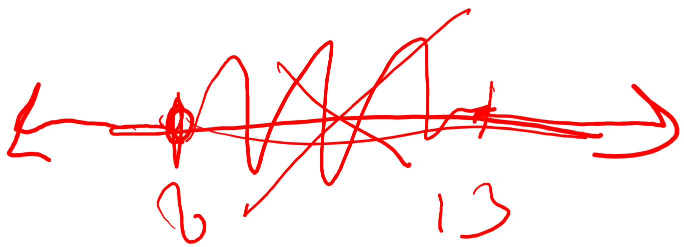
Credits: (Hinterberger et al., 2003)

Filters

- High Pass Filter:
  - Blocks dc offset in high gain amplifiers or single supply circuits. Filters can be used to separate signals, passing those of interest, and attenuating the unwanted frequencies.
- Low Pass Filter:
  - Stabilizes amplifiers by rolling off the gain at higher frequencies where excessive phase shift may cause oscillations

Filters

- Band Pass Filter:
  - If a high-pass filter and a low-pass filter are cascaded, a band pass filter is created. The band pass filter passes a band of frequencies between a lower cutoff frequency, f_L, and an upper cutoff frequency, f_h
- Notch (Band Reject Filter):
  - The pass bands include frequencies below f_L and above f_h. The band from f_L to f_h is in the stop band.



TIME DOMAIN ANALYSIS

① Hjorth Parameters [1970s] ← EEG $s(t)$

- → Mean Power
- → RMS freq.
- → RMS freq. spread

ⓐ Activity

$A = a_0$

a_0: variance of signal in the epoch under measurement

ⓑ Motility

$$M = \sqrt{\frac{a_2}{a_0}}$$

a_2 = variance of $\frac{ds(t)}{dt}$

③ Complexity

$$C = \sqrt{\frac{a_4}{a_0}}$$

a_4: variance of $\frac{d^2 s(t)}{dt^2}$

② Auto Regressive Modeling (AR)

$$\underline{x_t} = \sum_{i=1}^{p} \underline{a_i}\, \underline{x_{t-i}} + \epsilon_t$$

ϵ_t :- Some white noise

p :- Order of AR model

Adaptive Auto Regressive (AAR) Model.

$$\underline{\underline{x_t}} = \sum_{i=1}^{p} \underline{\underline{a_{i,t}}}\, x_{t-i} + \epsilon_t$$

Statistical Structure over time

Spatial Filtering

Spatial Filtering

- Spatial filtering techniques take as input brain signals recorded from several different locations (or "channels") and transform them in one of several ways.
- Possible goals include
    - enhancing local activity
    - reducing noise that is common across channels,
    - decreasing the dimensionality of the data,
    - finding projections that maximize discrimination between different classes

Bipolar

- Extract bipolar signals

$$\widetilde{s_{i,j}} = s_i - s_j$$

- Highlight the **electrical potential differences** between the two electrodes of interest (i and j).

Laplacian

- *Laplacian filtering*, extracts local activity at electrode *i* by subtracting the average activity present in the four orthogonal nearest neighboring electrodes

$$\tilde{s} = s_i - \frac{1}{4}\sum_{i \in \theta} s_i$$

Common Average Referencing

- *Common average referencing* (CAR), enhances the local activity at electrode *i* by subtracting the average over all electrodes

$$\widetilde{\boldsymbol{s}}_{\boldsymbol{i}} = \boldsymbol{s}_{\boldsymbol{i}} - \frac{\mathbf{1}}{\boldsymbol{N}} \sum_{\boldsymbol{i}=\mathbf{1}}^{\boldsymbol{N}} \boldsymbol{s}_{\boldsymbol{i}}$$

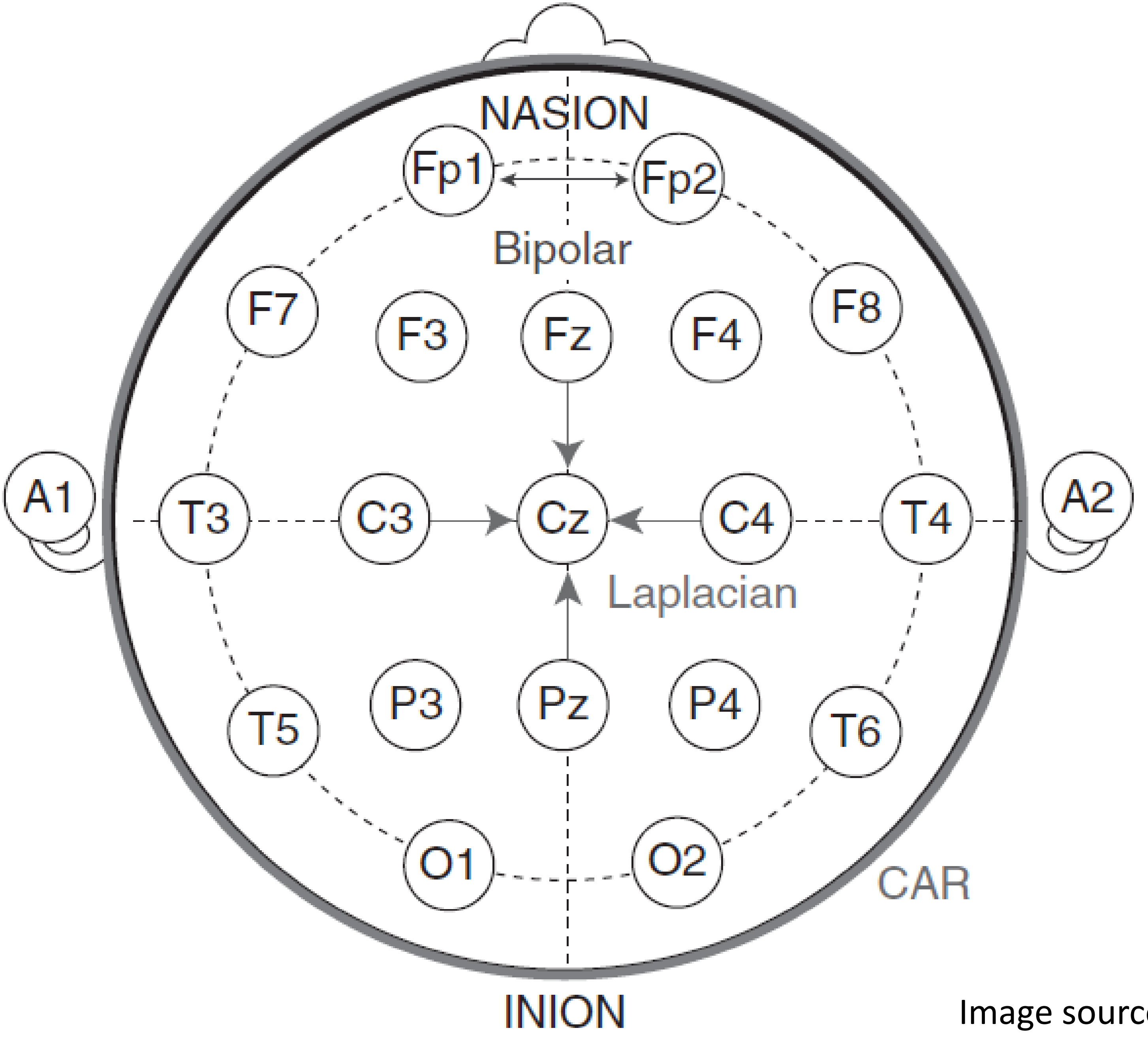


Image source: Rajesh P.N, Rao- Brain Computer Interfacing: An Introduction

Vector Representation

- A vector **x** ϵ R^n can be represented by n components:

$$\mathbf{x}: \begin{bmatrix} x_1 \\ x_2 \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ x_N \end{bmatrix}$$

- Assuming the standard base <v_1, v_2, …, v_N> (i.e., unit vectors in each dimension), x_i can be obtained by projecting **x** along the direction of v_i:

$$x_i = \frac{\mathbf{x}^T v_i}{v_i^T v_i} = \mathbf{x}^T v_i$$

- **x** can be "reconstructed" from its projections as follows:

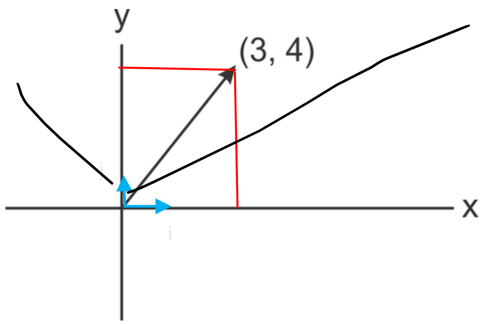
$$\mathbf{x} = \sum_{i=1}^{N} x_i v_i = x_1 v_1 + x_2 v_2 + \ldots + x_N v_N$$

- Since the basis vectors are the same for all x ϵ R^n (standard basis), we typically represent them as a n-component vector.

Vector Representation (cont'd)

- **Example** assuming n=2:

$$\mathbf{x}: \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} 3 \\ 4 \end{bmatrix}$$



- Assuming the standard base <v_1=i, v_2=j>, x_i can be obtained by projecting x along the direction of v_i:

$$x_1 = \mathbf{x}^T i = \begin{bmatrix} 3 & 4 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} = 3$$

$$x_2 = \mathbf{x}^T j = \begin{bmatrix} 3 & 4 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \end{bmatrix} = 4$$

- **x** can be "reconstructed" from its projections as follows:

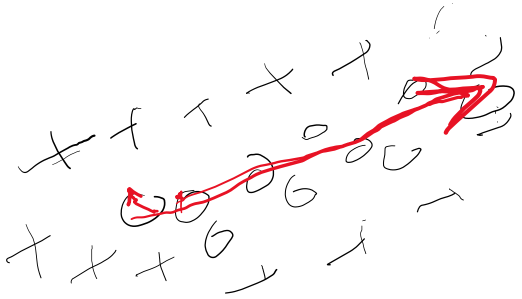
$$\mathbf{x} = 3i + 4j$$

Principal Component Analysis

- The goal in *principal component analysis* (PCA) (also called the *Karhunen-Loeve* or *Hotelling transform*) is to discover the underlying statistical variability in the data and reduce the data's dimensionality from D to a much smaller number of dimensions L ($L \ll D$).

- PCA achieves this goal by
  - Finding the directions of maximum variance in the D-dimensional data
  - Rotating the original coordinate system to align with these directions of maximum variance

Principal Component Analysis



- Most natural signals, including brain signals are redundant
- In the case of EEG measurements from N electrodes
  - Measurements from nearby electrodes may be correlated
  - Underlying rhythms across multiple electrodes.
- PCA attempts to find the dominant directions of variability in the data.
- New data points can be projected along the “principal” directions. Each projection is called a “principal component”
- The resulting *L*-dimensional vector can be used as a feature vector for classification or other purposes in BCI applications

Principal Component Analysis (PCA)

- If $\mathbf{x} \in R^N$, then it can be written a linear combination of an orthonormal set of N basis vectors $<v_1, v_2, \ldots, v_N>$ in R^N (e.g., using the standard base):

$$v_i^T v_j = \begin{cases} 1 & \text{if } i = j \\ 0 & \text{otherwise} \end{cases}$$

$$\mathbf{x} = \sum_{i=1}^{N} x_i v_i = x_1 v_1 + x_2 v_2 + \ldots + x_N v_N$$

$$\text{where} \quad x_i = \frac{\mathbf{x}^T v_i}{v_i^T v_i} = \mathbf{x}^T v_i$$

$$\mathbf{x}: \begin{bmatrix} x_1 \\ x_2 \\ . \\ . \\ . \\ . \\ . \\ x_N \end{bmatrix}$$

- PCA seeks to approximate $\mathbf{x}$ in a subspace of R^N using a new set of K<<N basis vectors $<u_1, u_2, \ldots, u_K>$ in R^N:

$$\hat{\mathbf{x}} = \sum_{i=1}^{K} y_i u_i = y_1 u_1 + y_2 u_2 + \ldots + y_K u_K \quad \text{where} \quad y_i = \frac{\mathbf{x}^T u_i}{u_i^T u_i} = \mathbf{x}^T u_i$$

(reconstruction)

$$\hat{\mathbf{x}}: \begin{bmatrix} y_1 \\ y_2 \\ . \\ . \\ y_K \end{bmatrix}$$

such that $\| \mathbf{x} - \hat{\mathbf{x}} \|$ is minimized!

(i.e., minimize information loss)

Principal Component Analysis (PCA)

- The "optimal" set of basis vectors $<u_1, u_2, \ldots, u_K>$ can be found as follows (we will see why):

(1) Find the eigenvectors u_i of the covariance matrix of the (training) data Σ_x

$$\Sigma_x u_i = \lambda_i u_i$$

(2) Choose the K "largest" eigenvectors u_i (i.e., corresponding to the K "largest" eigenvalues λ_i)

$<u_1, u_2, \ldots, u_K>$ correspond to the "optimal" basis!

We refer to the "largest" eigenvectors u_i as principal components.

PCA - Steps

- Suppose we are given $\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_M$ (N x 1) vectors

N: # of features

M: # data

Step 1: compute sample mean

$$\bar{\mathbf{x}} = \frac{1}{M}\sum_{i=1}^{M} \mathbf{x}_i$$

Step 2: subtract sample mean (i.e., center data at zero)

$$\Phi_i = \mathbf{x}_i - \bar{\mathbf{x}}$$

Step 3: compute the sample covariance matrix Σ_x

$$\Sigma_{\mathbf{x}} = \frac{1}{M}\sum_{i=1}^{M}(\mathbf{x}_i - \bar{\mathbf{x}})(\mathbf{x}_i - \bar{\mathbf{x}})^T = \frac{1}{M}\sum_{i=1}^{M}\Phi_i\Phi_i^T = \frac{1}{M}AA^T$$

where $A=[\Phi_1\ \Phi_2\ \ldots\ \Phi_M]$

i.e., the columns of A are the Φ_i

(N x M matrix)

PCA - Steps

Step 4: compute the eigenvalues/eigenvectors of Σ_x

$$\Sigma_x u_i = \lambda_i u_i$$

where we assume $\lambda_1 > \lambda_2 > \ldots > \lambda_N$

Note : most software packages return the eigenvalues (and corresponding eigenvectors) is decreasing order – if not, you can explicitly put them in this order)

Since Σ_x is symmetric, $\langle u_1, u_2, \ldots, u_N \rangle$ form an orthogonal basis in R^N and we can represent any $\mathbf{x} \in R^N$ as:

$$\mathbf{x} - \bar{\mathbf{x}} = \sum_{i=1}^{N} y_i u_i = y_1 u_1 + y_2 u_2 + \ldots + y_N u_N$$

$$y_i = \frac{(\mathbf{x} - \bar{\mathbf{x}})^T u_i}{u_i^T u_i} = (\mathbf{x} - \bar{\mathbf{x}})^T u_i \qquad if \ \ \|u_i\| = 1$$

i.e., this is just a "change" of basis!

$$\mathbf{x} - \bar{\mathbf{x}} : \begin{bmatrix} x_1 \\ x_2 \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ x_N \end{bmatrix} \rightarrow \begin{bmatrix} y_1 \\ y_2 \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ y_N \end{bmatrix}$$

Note : most software packages normalize u_i to unit length to simplify calculations; if not, you can explicitly normalize them)

PCA - Steps

Step 5: dimensionality reduction step – approximate **x** using only the first K eigenvectors (K<<N) (i.e., corresponding to the K largest eigenvalues where K is a parameter):

$$\mathbf{x}-\bar{\mathbf{x}}=\sum_{i=1}^{N} y_i u_i = y_1u_1+y_2u_2+\ldots+y_Nu_N$$

N → K

approximate $\mathbf{x}$ *by* $\hat{\mathbf{x}}$
using first K eigenvectors only

$$\hat{\mathbf{x}}-\bar{\mathbf{x}}=\sum_{i=1}^{K} y_i u_i = y_1u_1+y_2u_2+\ldots+y_Ku_K$$

(reconstruction)

$$\mathbf{x}-\bar{\mathbf{x}}: \begin{bmatrix} x_1 \\ x_2 \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ x_N \end{bmatrix} \rightarrow \begin{bmatrix} y_1 \\ y_2 \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ y_N \end{bmatrix} \rightarrow \hat{\mathbf{x}}-\bar{\mathbf{x}}: \begin{bmatrix} y_1 \\ y_2 \\ \cdot \\ \cdot \\ y_K \end{bmatrix}$$

note that if K=N, then $\hat{\mathbf{x}}=\mathbf{x}$
(i.e., zero reconstruction error)

What is the Linear Transformation implied by PCA?

- The linear transformation y = Tx which performs the dimensionality reduction in PCA is:

$$\hat{\mathbf{x}} - \bar{\mathbf{x}} = \sum_{i=1}^{K} y_i u_i = y_1 u_1 + y_2 u_2 + \ldots + y_K u_K$$

$$(\hat{\mathbf{x}} - \bar{\mathbf{x}}) = U \begin{bmatrix} y_1 \\ y_2 \\ . \\ . \\ y_K \end{bmatrix}$$

$$where\ U = [u_1\, u_2 \ldots u_K] \quad N\, x\, K \text{ matrix}$$

i.e., the columns of U are the the first K eigenvectors of Σ_x

$$\begin{bmatrix} y_1 \\ y_2 \\ . \\ . \\ y_K \end{bmatrix} = U^T (\hat{\mathbf{x}} - \bar{\mathbf{x}})$$

$T = U^T$ K x N matrix

i.e., the rows of T are the first K eigenvectors of Σ_x

What is the form of Σ_y ?

$$\Sigma_{\mathbf{x}} = \frac{1}{M}\sum_{i=1}^{M}(\mathbf{x}_{\mathrm{i}} - \overline{\mathbf{x}})(\mathbf{x}_{\mathrm{i}} - \overline{\mathbf{x}})^T = \frac{1}{M}\sum_{i=1}^{M}\Phi_i\Phi_i^T$$

Using diagonalization:

$$\Sigma_{\mathbf{x}} = P\Lambda P^T$$

The columns of P are the eigenvectors of Σ_X

The diagonal elements of Λ are the eigenvalues of Σ_X or the variances

$$\mathbf{y}_i = U^T(\mathbf{x}_i - \overline{\mathbf{x}}) = P^T\Phi_i$$

$$\Sigma_{\mathbf{y}} = \frac{1}{M}\sum_{i=1}^{M}(\mathbf{y}_{\mathrm{i}} - \overline{\mathbf{y}})(\mathbf{y}_{\mathrm{i}} - \overline{\mathbf{y}})^T = \frac{1}{M}\sum_{i=1}^{M}(\mathbf{y}_{\mathrm{i}})(\mathbf{y}_{\mathrm{i}})^T = \frac{1}{M}\sum_{i=1}^{M}(P^T\Phi_i)(P^T\Phi_i)^T =$$

$$\frac{1}{M}\sum_{i=1}^{M}(P^T\Phi_i)(\Phi_i^T P) = P^T(\frac{1}{M}\sum_{i=1}^{M}\Phi_i\Phi_i^T)P = P^T\Sigma_{\mathbf{x}}P = P^T(P\Lambda P^T)P = \Lambda$$

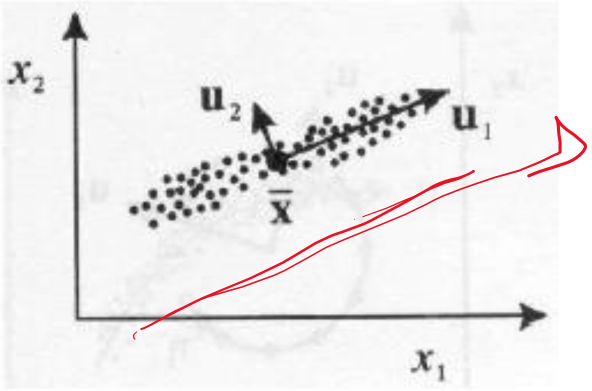
$$\boxed{\Sigma_{\mathbf{y}} = \Lambda}$$

PCA de-correlates the data!

Preserves original variances!

Interpretation of PCA

- PCA chooses the eigenvectors of the covariance matrix corresponding to the largest eigenvalues.
- The eigenvalues correspond to the variance of the data along the eigenvector directions.
- Therefore, PCA projects the data along the directions where the data varies most.
- PCA preserves as much information in the data by preserving as much variance in the data.



u_1: direction of max variance
u_2: orthogonal to u_1

Example

- Compute the PCA of the following dataset:

(1,2),(3,3),(3,5),(5,4),(5,6),(6,5),(8,7),(9,8)

- Compute the sample covariance matrix is:

$$\hat{\Sigma} = \frac{1}{n}\sum_{k=1}^{n}(\mathbf{x}_k - \hat{\boldsymbol{\mu}})(\mathbf{x}_k - \hat{\boldsymbol{\mu}})^t$$

$$\Sigma_x = \begin{bmatrix} 6.25 & 4.25 \\ 4.25 & 3.5 \end{bmatrix}$$

- The eigenvalues can be computed by finding the roots of the characteristic polynomial:

$$\Sigma_x v = \lambda v \Rightarrow |\Sigma_x - \lambda I| = 0$$
$$\Rightarrow \begin{vmatrix} 6.25 - \lambda & 4.25 \\ 4.25 & 3.5 - \lambda \end{vmatrix} = 0$$
$$\Rightarrow \boldsymbol{\lambda_1 = 9.34; \lambda_2 = 0.41}$$

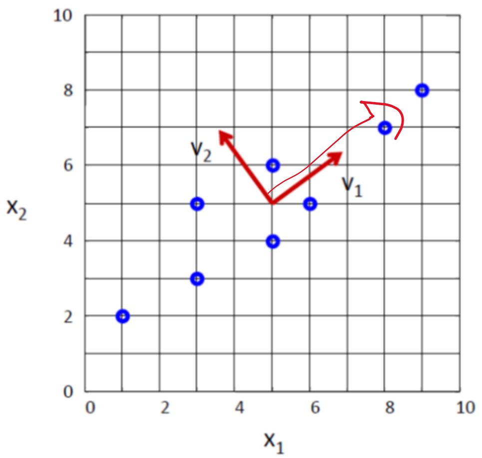
Example (cont'd)

- The eigenvectors are the solutions of the systems:

$$\Sigma_{\mathbf{x}} u_i = \lambda_i u_i$$

$$\begin{bmatrix} 6.25 & 4.25 \\ 4.25 & 3.5 \end{bmatrix} \begin{bmatrix} v_{11} \\ v_{12} \end{bmatrix} = \begin{bmatrix} \lambda_1 v_{11} \\ \lambda_1 v_{12} \end{bmatrix} \Rightarrow \begin{bmatrix} v_{11} \\ v_{12} \end{bmatrix} = \begin{bmatrix} 0.81 \\ 0.59 \end{bmatrix}$$

$$\begin{bmatrix} 6.25 & 4.25 \\ 4.25 & 3.5 \end{bmatrix} \begin{bmatrix} v_{21} \\ v_{22} \end{bmatrix} = \begin{bmatrix} \lambda_2 v_{21} \\ \lambda_2 v_{22} \end{bmatrix} \Rightarrow \begin{bmatrix} v_{21} \\ v_{22} \end{bmatrix} = \begin{bmatrix} -0.59 \\ 0.81 \end{bmatrix}$$



Note: if u_i is a solution, then cu_i is also a solution where $c \neq 0$.

Eigenvectors can be normalized to unit-length using:

$$\hat{v}_i = \frac{v_i}{\| v_i \|}$$

How do we choose K ?

- *K* is typically chosen based on how much information (variance) we want to preserve:

Choose the smallest K that satisfies the following inequality:

$$\frac{\sum_{i=1}^{K} \lambda_i}{\sum_{i=1}^{N} \lambda_i} > T \quad where\ T\ is\ a\ threshold\ (e.g., 0.9)$$

- If T=0.9, for example, we "preserve" 90% of the information (variance) in the data.

- If K=N, then we "preserve" 100% of the information in the data (i.e., just a "change" of basis and $\hat{\mathbf{x}} = \mathbf{x}$)

Approximation Error

- The approximation error (or reconstruction error) can be computed by:

$$\| \mathbf{x} - \hat{\mathbf{x}} \|$$

where $$\hat{\mathbf{x}} = \sum_{i=1}^{K} y_i u_i + \overline{\mathbf{x}} = y_1 u_1 + y_2 u_2 + \ldots + y_K u_K + \overline{\mathbf{x}}$$

(reconstruction)

- It can also be shown that the approximation error can be computed as follows:

$$\| \mathbf{x} - \hat{\mathbf{x}} \| = \frac{1}{2} \sum_{i=K+1}^{N} \lambda_i$$

Data Normalization

- The principal components are dependent on the *units* used to measure the original variables as well as on the *range* of values they assume.

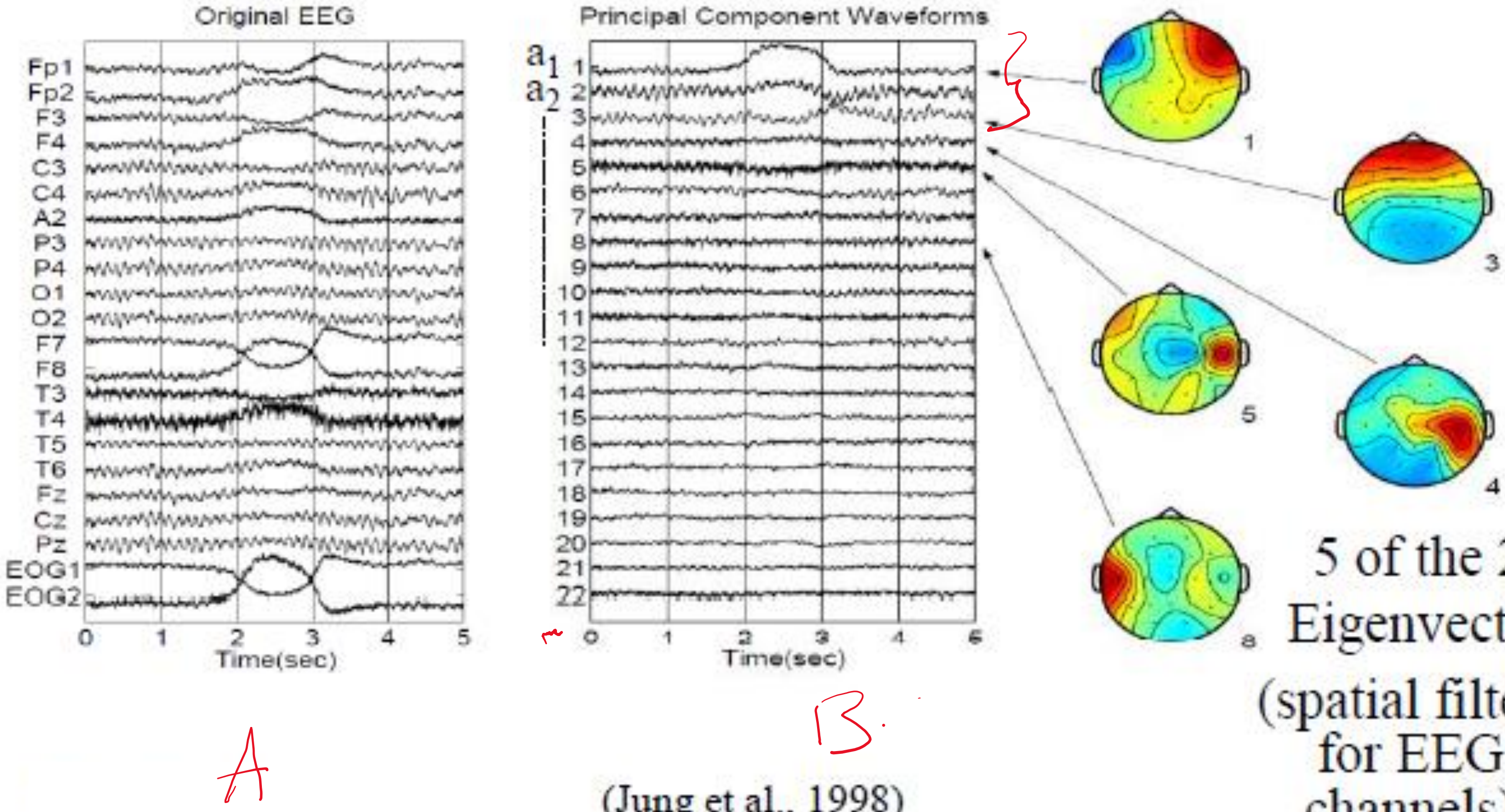
- Data should always be normalized prior to using PCA.

- A common normalization method is to transform all the data to have zero mean and unit standard deviation:

$$\frac{x_i - \mu}{\sigma}$$

where μ and σ are the mean and standard deviation of the i-th feature x_i

PCA applied to EEG



5 of the 22 Eigenvectors (spatial filters for EEG channels)

(Jung et al., 1998)

Independent Component Analysis

- PCA finds a matrix **V** that decorrelates the inputs but the resulting feature vector ***a*** may still retain higher order statistical dependencies
- There may be a possibility that the variables are independent.
- ICA tries to find a matrix W of filters (columns of W) such that the output **a** is **statistically independent**:

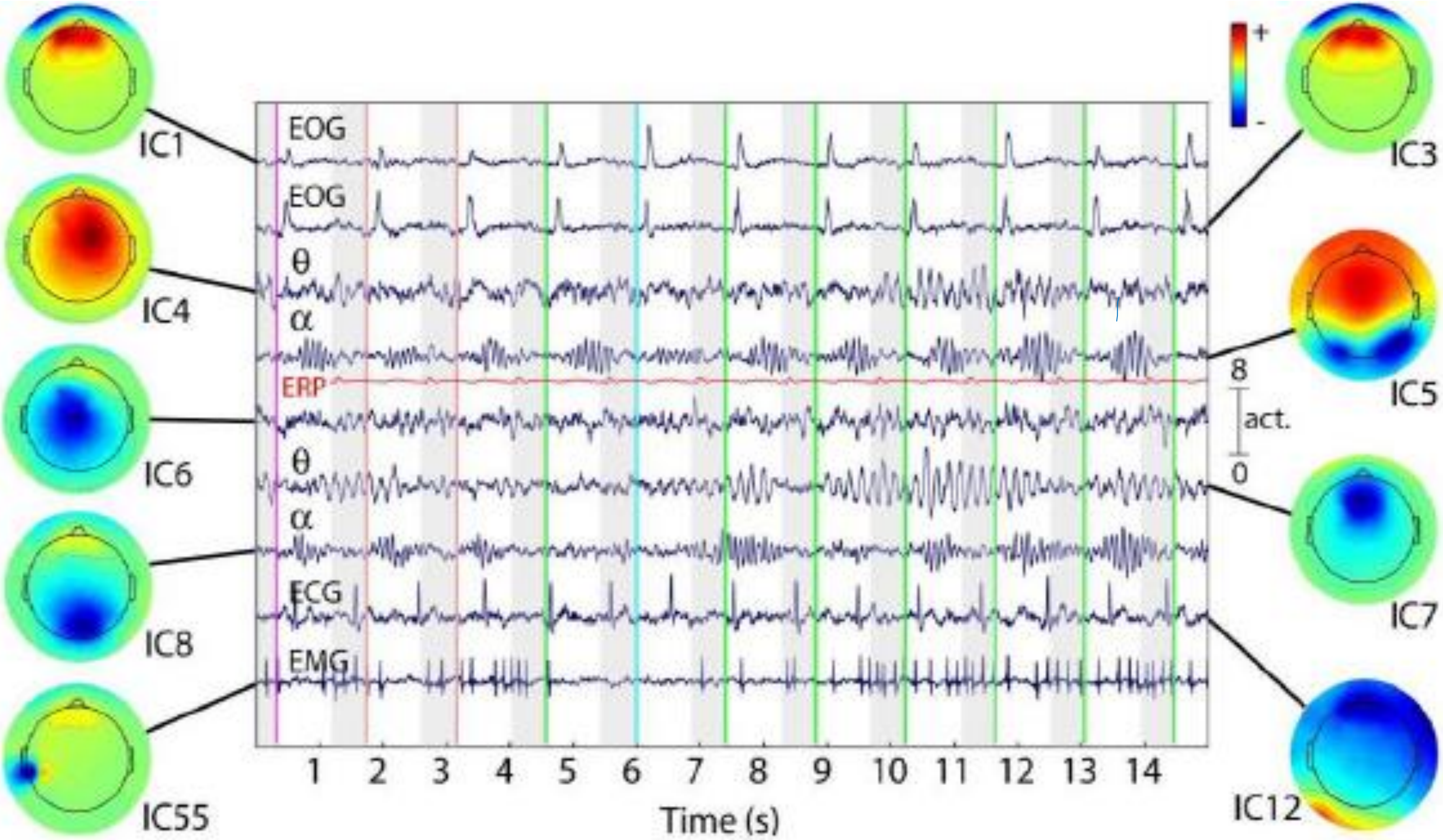
$$\boldsymbol{a} = \boldsymbol{W}^{\boldsymbol{T}}\boldsymbol{x} \text{ such that } \boldsymbol{P}(\boldsymbol{a}) \approx \prod_{\boldsymbol{i}=\boldsymbol{1}}^{\boldsymbol{D}} \boldsymbol{P}(\boldsymbol{a}_{\boldsymbol{i}})$$

Independent Component Analysis

- ICA assumes sources are linearly mixed to produce x

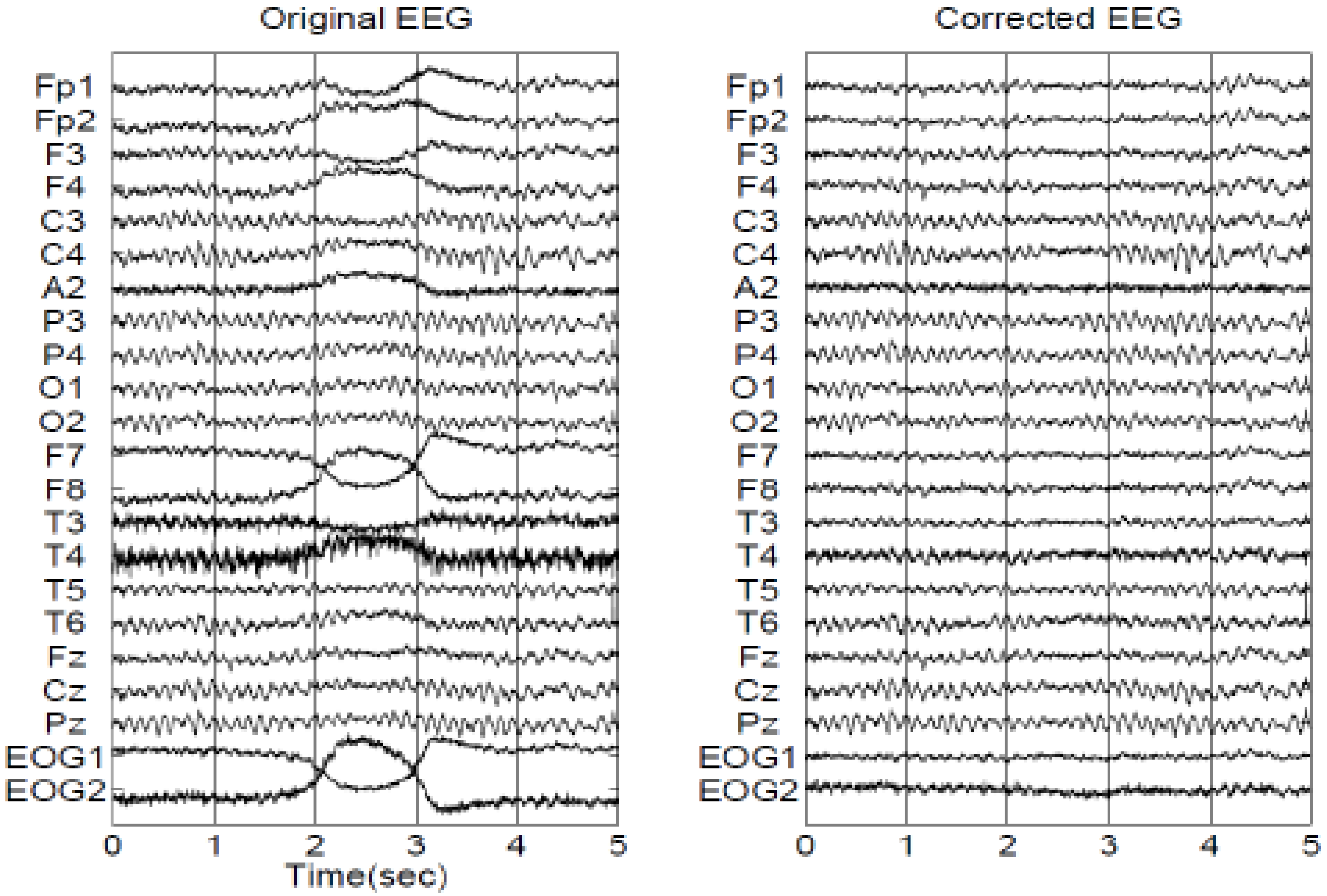
- The feature vector dimension in ICA can be lesser than, equal to, or greater than the number of input dimensions.

- ICA has proved useful in a variety of settings in BCI applications, ranging from the use of the output vector **a** as a feature vector in classification.



Application of ICA to EEG data for isolating electro- oculographic (EOG) (eye-related), electromyographic (EMG) (muscle-related) and electrocardiographic (ECG) (heart-related) artifacts, and unmixing putative source signals in the brain. Image (adapted from Onton and Makeig, 2006)

ICA for Artifact Removal in EEG



Common Spatial Pattern

- Supervised Technique
- Data is labeled with class to which each data vector belongs
  - E.g., EEG obtained for right versus left hand imagery
- CSP finds a matrix of spatial filters
  - the variance of the filtered data for one class is maximized
  - variance of the filtered data for the other class is minimized
- CSP filters can significantly enhance discrimination ability between the two classes

Common Spatial Pattern

$$\begin{array}{c|ccc} & Ch\text{-}1 & Ch\text{-}2 & Ch\text{-}3 \\ \hline 1 & 2.5 & 3.5 & 4.5 \\ 2 & 0.3 & 8.8 & 1.9 \\ 3 & \vdots & \vdots & \vdots \end{array} \quad N \times T$$

<u>Input</u> : $\{X_c^i\}_{i=1}^{K}$ C: classes, i: trial, K: no. of trials.

$X_c^i \rightarrow N \times T$ [No. of channels + Time samples]

X - Matrix

x - vector

Assuming X_c^i is centered & scaled

<u>Goal</u>:- Spatial filter Matrix 'W' $\rightarrow N \times M$

Transform signal according to eqn.-

$$x_{csp}(t) = \underline{\underline{W^T}}\, x(t) \quad \text{—— (1)}$$

Common Spatial Pattern

Two class conditional covariance matrix

$$R_c = \frac{1}{K} \sum_i X_c^i (X_c^i)^T \quad \text{for } c \in [1,2]$$

determine W as

$$W^T R_1 W = \Lambda_1$$

$$W^T R_2 W = \Lambda_2$$

$$\begin{bmatrix} \lambda_1 & & & \\ & \lambda_2 & & \\ & & \ddots & \\ & & & \lambda_i \end{bmatrix}$$

$$\Lambda_1 + \Lambda_2 = I$$

$$R_1 w = \lambda R_2 w$$

Generalized eigenvalue

$$\lambda_1^j = w_j^T R_1 w_j \rightarrow \Lambda_1$$

$$\lambda_2^j = w_j^T R_2 w_j \rightarrow \Lambda_2$$

$$\lambda_1^j + \lambda_2^j = 1$$

High value

High variance

Low value

Low variance

Classifier

CSP applied to EEG for Right/Left Hand Imagery

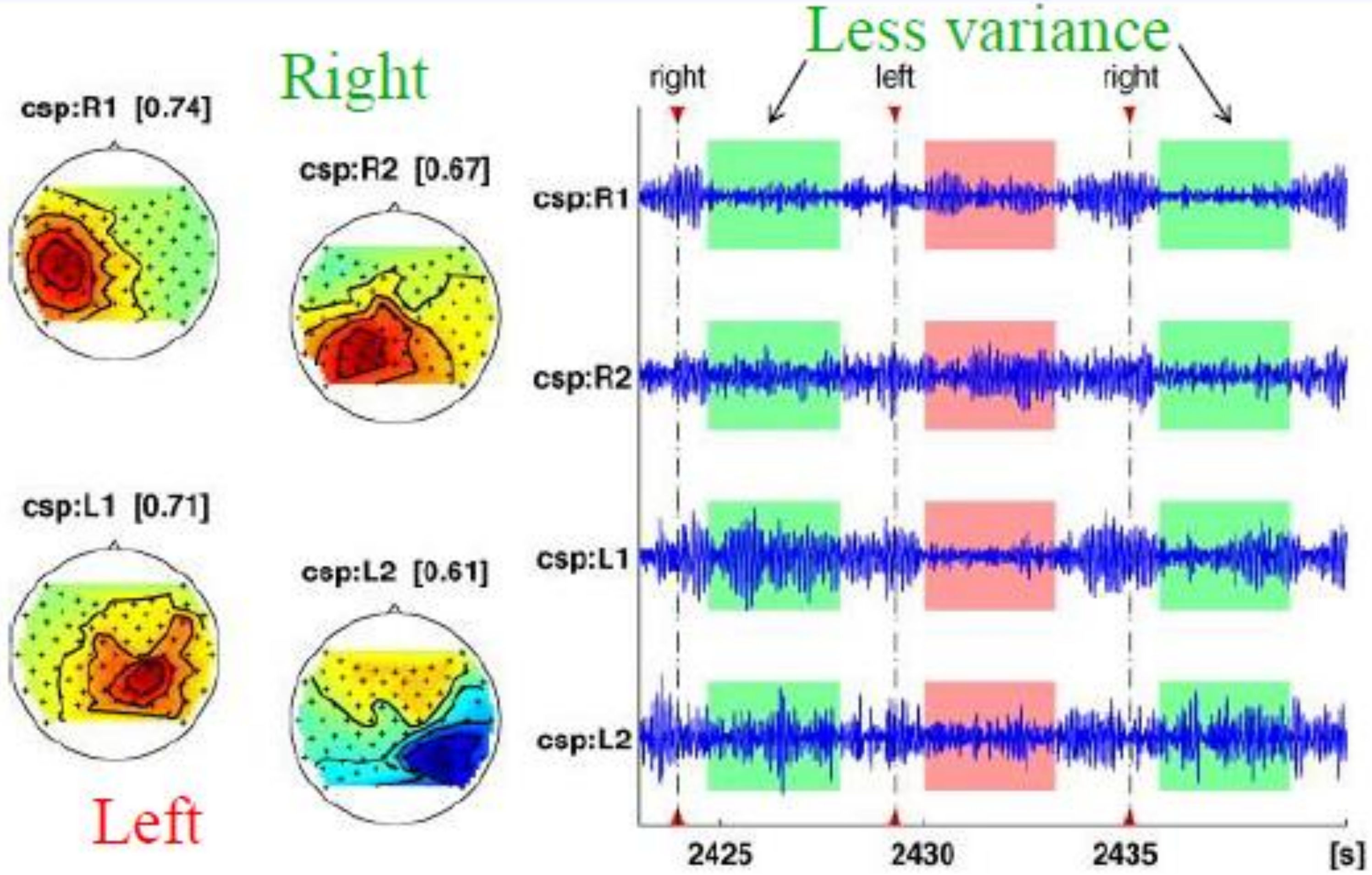


Image source: http://www.sciencedirect.com/science/article/pii/S0165027007004657

Artifact Reduction Techniques

- Artifacts in BCIs are any undesirable signals
  - Artifacts outside body-50/60Hz
    - Power line
    - External electrical interference
  - Artifacts within body
    - Rhythmic artifacts due to respiration and heartbeat (the latter are called electrocardiographic or ECG artifacts
    - Signal distortion or attenuation due to skin conductance changes
    - Eye movement and eye blink artifacts (also called electro-oculographic or EOG artifacts)-- range 3–4Hz
    - Muscle artifacts (electromyographic or EMG artifacts)-- 30Hz or higher frequency range.

Artifact Reduction Techniques

- Thresholding
  - If the magnitude or some other characteristic of a recorded EOG or EMG signal exceeds a pre-determined threshold, the brain signals recorded during that epoch are deemed to be contaminated and rejected.
- Band-Stop and Notch Filtering
  - Band-stop filtering is a useful artifact reduction technique that attenuates the components of a signal in a specific frequency band and passes the rest of the components of the signal.
  - A notch filter set to the 59–61 Hz band (in the United States) for filtering out the 60 Hz power-line noise artifact.

Artifact Reduction Techniques

- Linear Modeling
  - A simple way of modeling the effect of artifacts on a recorded brain signal is to assume that the effect is additive.
  - For example, if $EEG_i(t)$ is the EEG signal recorded from electrode *i* at time *t*, then a model of how the signal has been contaminated could be:

$$EEG_i(t) = EEG_i^{true}(t) + K \cdot EOG(t)$$

  - EEG_i^{true}(t) is the uncontaminated (“true”) EEG signal from electrode *i* at time *t*, $EOG(t)$ is the recorded EOG signal at time *t* and *K* is a constant.
  - Given an estimated value for K, one can obtain an estimate of the true EEG signal using:

$$EEG_i^{true}(t) = EEG_i(t) - K \cdot EOG(t)$$